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COMMUNICATIONS - ELECTRONIC INTRASYSTEM ELECTROMAGNETIC INTERFERENCE MEASUREMENT TECHNIQUES AND INSTRUMENTATION

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INTERFERENCE MEASUREMENT	MIL-STD-461 LIMITS
EMC ANALYSIS TECHNIQUES	DISTANCE TRANSFER FUNCTION
EMC MEASUREMENT TECHNIQUES	EMC MEASUREMENT STANDARD

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report concludes the results obtained during the Communications-Electronics Intrasystem Electromagnetic Interference Measurement Techniques and Instrumentation Project. The period covered was 20 June 1979 to 20 June 1980. The major effort consisted of an IEMCAP feasibility study, development of a broadband measurement technique from below 14 kHz to over 100 GHz, development of a distance transfer function accurate in both the near and far field and preparation of a draft Intrasystem EMC Measurement Standard.

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1. INTRODUCTION

The purpose of this contract is to develop an improved approach to the communication-electronic system integration problem from an electromagnetic interference (EMI) standpoint. Specifically, the effort is directed toward investigating the use of broadband measurement techniques and computerized analytical tools such as the Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP) in conjunction with the overall electromagnetic compatibility (EMC) test procedures of MIL-STD-461 and -462 to develop a more meaningful and economical approach to defining the system EMI problems. The analytical techniques will provide guidance and insight into the system characteristics which will allow for effective utilization of measurement resources and time. The results will lead to the establishment of an interactive EMI/EMC analysis and measurement procedure which will provide the basis for a meaningful EMI intrasystem measurement standard. In developing this procedure, an attempt was made to limit the measurement requirements to those which are necessary and at the same time sufficient to ensure electromagnetic compatibility.

The effort is divided into three categories (Analysis, Measurements, and EMI/EMC Considerations) which are divided into subtasks as shown below.

<u>Analysis Substasks</u>

- Definition of Equipment Parameter Data needed for IEMCAP inputs.
- Limitations of IEMCAP program.
- Applicability of IEMCAP to systems analysis.

<u>Measurement Subtasks</u>

- The use of pre-detection and post-detection bandwidth control to establish an Impulse/CW Response Ratio that enables narrowband and broadband measurements to be combined into a single measurement.

- Evaluation of the accuracy obtainable with Broadband Measurement Techniques.
- Improved means for extrapolation of measurement distances so that data obtained from radiated measurements may be applied to other distances than those actually used in the measurements.

EMI/EMC Considerations

- Presentation of a draft Intrasystem Measurement Standard that utilizes the techniques of analysis and measurement developed in this task.
- Develop a plan to verify the methodology presented.

This report is the final report on the subject contract. A summary of the major project accomplishments, recommendations, and conclusions is presented in Section 2.0. A detailed description of the work performed during the fourth and final quarter is presented in Section 3.0. Appendices I and II present a draft Intrasystem Measurement Standard and a Recommended Test Program for Validating the Methodology.

2. SUMMARY AND CONCLUSIONS

The present method of incorporating EMC considerations into system design consists of applying the rigid limits of MIL-STD-461A to the individual equipments/subsystems which comprise the total system. Compliance with these limits is ensured by testing the individual units in accordance with MIL-STD-462. Total system EMC is ensured by performing system tests which investigate every potential EMI susceptibility of the actual system via the mechanisms inherent in the actual system in accordance with the requirements of MIL-E-6051D.

Although the present approach does ensure that EMC considerations are incorporated into system design, it often proves to be costly and time consuming. Some of the specific problems with the present approach to overall system EMC result from the fact that the standards are general. Therefore, the application of these standards to a specific system does not guarantee system EMC and in many cases will result in considerable over-design or under-design. Also, because the standards are general, their application to a specific system may result in considerable unnecessary testing.

To illustrate some of the problems associated with the concept of applying MIL-STD-461 type limits to equipments that will be used in a specific type of system consider the situation shown in Figure 1. This figure shows that the Radiated Susceptibility Limits (RS03 & RS04) are 120 dB/μV/meter while the Radiated Emission Limits (RE02) range from 20 dB/μV/meter to 60 dB/μV/meter. This means that there is a 60 dB to 100 dB difference between allowable unrequired emissions and susceptibilities. Part of the rationale behind the large difference between radiated emission and susceptibility limits is that the radiated susceptibility limits are intended to protect the equipments against intentional radiations which may be present within the system and the radiated emission limits are intended to

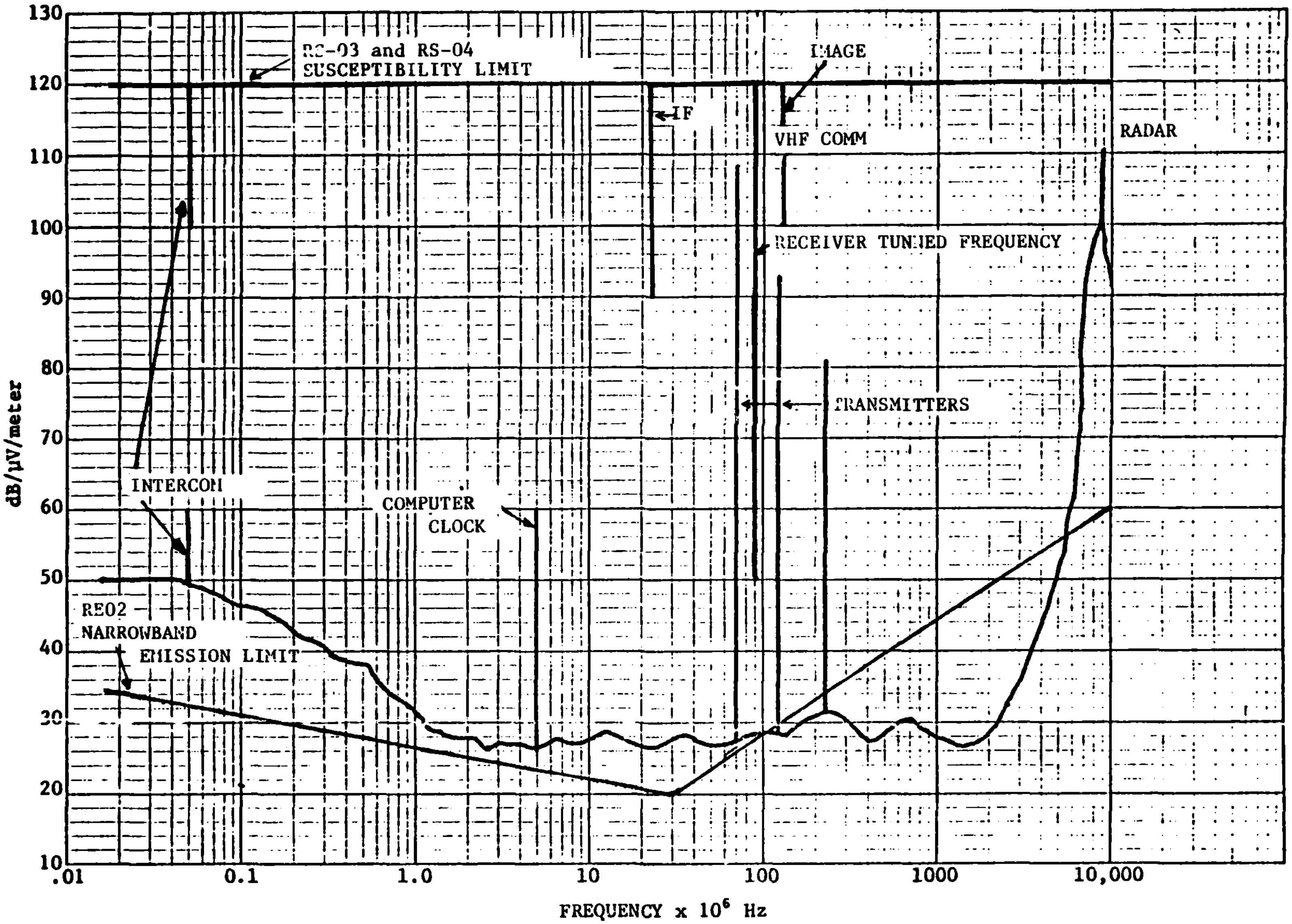

Figure 1 Hypothetical Emission/Susceptibility Spectrum

protect against EMI at intentional receptor frequencies. The figure shows a hypothetical emission and susceptibility spectrum for a specific system to help illustrate the overall situation. Referring to the figure, it may be seen that relatively stringent limits are required at frequencies of intentional emissions or susceptibilities whereas the limits could be considerably relaxed over the remainder of the spectrum. This figure suggests "tailoring" the limits to the specific critical emission or receptor frequencies and establishing relaxed limits over the remainder of the frequency band. The efforts on this contract investigated the use of EMC analysis for defining EMC requirements at critical frequencies, and broadband measurement techniques for testing over the remainder of the frequency band to provide a more cost effective approach to system level EMC.

The use of a computer EMC analysis program, such as that provided by the IEMCAP, to identify critical system frequencies and to define the EMC requirements at those frequencies appears feasible. An in-depth look at the input data requirements for IEMCAP, limitations of the present program, and applicability of IEMCAP for analyzing the EMC of a given system is presented. The input data required for IEMCAP does not appear to be overly excessive in terms of the amount of data required to perform a system EMC analysis. However, some of the required data, e.g., out-of-band emissions and susceptibilities, or wire type and routing, may be difficult to obtain in the early stages of system development and thus there remains a questionable area that must be resolved. Also, a data collection philosophy needs to be established for Army system procurements.

There are several limitations associated with the present IEMCAP. These limitations in the program may be considered as resulting from the following:

- State-of-the-Art Modeling Capability
- Stringent Computer Requirements
- Air Force Systems Requirements

Overall the program limitations are as appropriate to applying IEMCAP to Army systems as they are to Air Force systems. However, it is recognized from this study that some modifications of the IEMCAP are necessary for handling Army systems. Modifications considered to date consist of the following:

- System Geometry Structure
- Antenna Coupling Models which Account for Diffraction and Shading Factors Associated with Army Structures
- Specfication Generation Philosophy

The overall result of the IEMCAP feasibility study to date is that the IEMCAP should be used as an integral part of the overall test procedure. Further study beyond this point is required in the following areas:

- Philosophy for using the IEMCAP
- Data collection with regard to Army System Procurements
- Other possible modifications to IEMCAP to make it more efficient for use by the Army

Some of the questions and problems associated with the above efforts will require inputs from Army personnel. Possibly, some actual experience on implementing the IEMCAP on an Army system will be required to provide the answers.

A system for performing broadband measurements of EMI over the range from below 14 kHz to above 100 GHz in eleven bands without tuning has been shown to be physically realizable. The output indication from such a system would be in units, such as decibels, relative to some specification limit. This implies that a threshold detector set at the specification limit would produce a go/no-go indication of the passage or failure of an EMI test of the general type presently required by MIL-STD-461. For such an indication to be meaningful without prior knowledge of the nature of the emissions, all of the ramifications of the measurement specification must be incorporated into the measurement hardware.

This will be possible only if a new Broadband Measurement Specification is written around measurement hardware designed to meet certain specific criteria.

The first criteria of importance is frequency response. The Broadband Measurement System is realizable with flat frequency response to conducted emissions over the range 14 kHz (or below) to 100 GHz (and above). This flat conducted response can then be translated to radiated response by superimposing broadband antenna factors which, because of physical limitations on antennas, will dictate the shape of the specification curves for radiated emissions. At the present state-of-the-art, antennas may be physically realized with flat antenna factors up to 100 MHz (active antennas) and with antenna factors which increase at the rate of 6 dB/octave (constant gain) above 100 MHz. Once band edges have been established (the band edges in the hypothetical Broadband Measurement System occur at 14 kHz, 0.1, 1, 4, 7, 10, 18, 26.5, 40, 60, 90 and 100 GHz), they will have to be standardized so that consistent results can be obtained when measuring broadband emissions which overlap the band edges.

The second criteria of importance is the ratio of narrowband to broadband responses. This ratio can be specified for CW and impulse signals and controlled by adjusting the ratio of predetection to post-detection bandwidth in a crystal-video receiver. The approximate bandwidths required can be calculated using equations presented herein. The actual system must incorporate adjustable post-detection bandwidths so that thresholds can be accurately set to CW and impulse signals during calibration. The responses to other types of signals should then fall into place. Digital filtering in a microcomputer would be ideal for the final bandwidth adjustment.

The third criteria of importance is dynamic range. The Broadband Measurement System should accept any type of signal for which there is a narrowband or broadband specification limit,

at the level corresponding to the limit, without saturation. Failure to do so will result in the system ignoring emissions which exceed the limit. Current technology in the area of low-1/f-noise Schottky-diode detectors is such that this criteria can probably be met for the worst case signals (impulses) up to 1 GHz, which is as high in frequency as current MIL-STD-461 carries broadband limits. Above 1 GHz, the system saturation point should be standardized so that consistent measurements can be made with varying hardware embodiments on marginally-broadband emissions having coherent bandwidths over 1 GHz.

While the hree basic criteria outlined above are of primary importance, secondary criteria such as sensitivity, false alarm rate (primarily a problem of adequate signal-to-noise ratios; it can be reduced by microcomputer analysis) and accuracy (continuous automatic calibration is recommended) are also important. A breadboard Broadband Measurement System should now be assembled and tested to demonstrate feasibility.

3. WORK ACCOMPLISHED IN THE FOURTH QUARTER

The work in the fourth quarter has extended the broadband measurement technique for emissions up to 100 GHz and has analyzed the accuracy attainable, has derived a distance transfer function that can be used for both near-field and far-field conditions, has produced a draft Intrasystem Measurement Standard, (APPENDIX I) and has defined a test program to experimentally verify the proposed measurement techniques. Components to assemble a broadband (or narrowband) measurement system are available off-the-shelf up to and beyond 100 GHz. Accuracies attainable are on the order of ± 4 dB, but can be improved to within ± 2 dB by the addition of frequency compensation.

Measurements made in a shielded enclosure at a standard measurement distance, such as one meter, can be extrapolated to other distances by using a transfer function which is exact for both near-field and far-field conditions, if a worst-case analysis neglecting possible opertune level reductions from factors such as reflections and large antenna size is acceptable. The distance transfer function reduces distance relationships to units of decibels relative to wavelength (dBλ) at the measurement frequency to avoid the complication of the usual cubic wave equations.

The draft Intrasystem Measurement Standard calls for the use of IEMCAP to analyze and predict intrasystem EMC problems. The susceptibility/emission margin is reduced to 10 dB for equipments having data profiles generated by actual measurement, while a 20 dB margin is required for data profiles generated by modeling.

A test program is recommended in which the sensitivity, dynamic range and accuracy of the Broadband Measurement System will be experimentally verified. A similar program is recommended in which the draft Intrasystem Measurement Standard is applied to a typical system to experimentally assess the problems of fulfilling the special data requirements of IEMCAP.

A. Extension of Broadband Measurement Techniques to 100 GHz

The hypothetical Broadband Measurement System developed in the Second and Third Quarterly Reports carried the broadband measurement technique up to 10 GHz. Above 10 GHz several things happen. A transition from coax to waveguide must be made somewhat before reaching 35 GHz, the upper limit for the APC-3.5 (compatible with SMA) connector which is the only practical coaxial connector in this frequency range. Practical wideband preamplifiers are only available up to 40 GHz, which limits the sensitivity achievable with crystal-video techniques above that frequency. Use of high-gain antennas (waveguide horns) becomes practical because of the short far-field distances.

In the following subsections, the crystal-video techniques used previously will first be carried up to over 100 GHz and analyzed for sensitivity. The Hypothetical Broadband Measurement Specification from the Second Quarterly Report will then be extended to 100 GHz. When the sensitivity achievable with crystal-video techniques proves to be inadequate above 40 GHz, an alternate technique, using frequency translation (fundamental mixing) into Band 3 (1 to 4 GHz) of the previously developed hypothetical Broadband Measurement System, will be shown to be capable of providing the sensitivity needed for practical EMI measurements.

1) Crystal-Video Techniques Above 10 GHz

A block diagram of a hypothetical Broadband Measurement System, using crystal-video techniques to cover the frequency range from 10 GHz to 140 GHz, is shown in Figure 2. The system is basically an extension of the Second Cut System of Figure 3 in the Third Quarterly report, which covered 14 kHz (and below) to 10 GHz. Although the microcomputer and associated indicator circuitry are repeated in the 10-140 GHz (High-Band) System for clarity, they could be shared with the 14 kHz to 10 GHz (Low-Band)

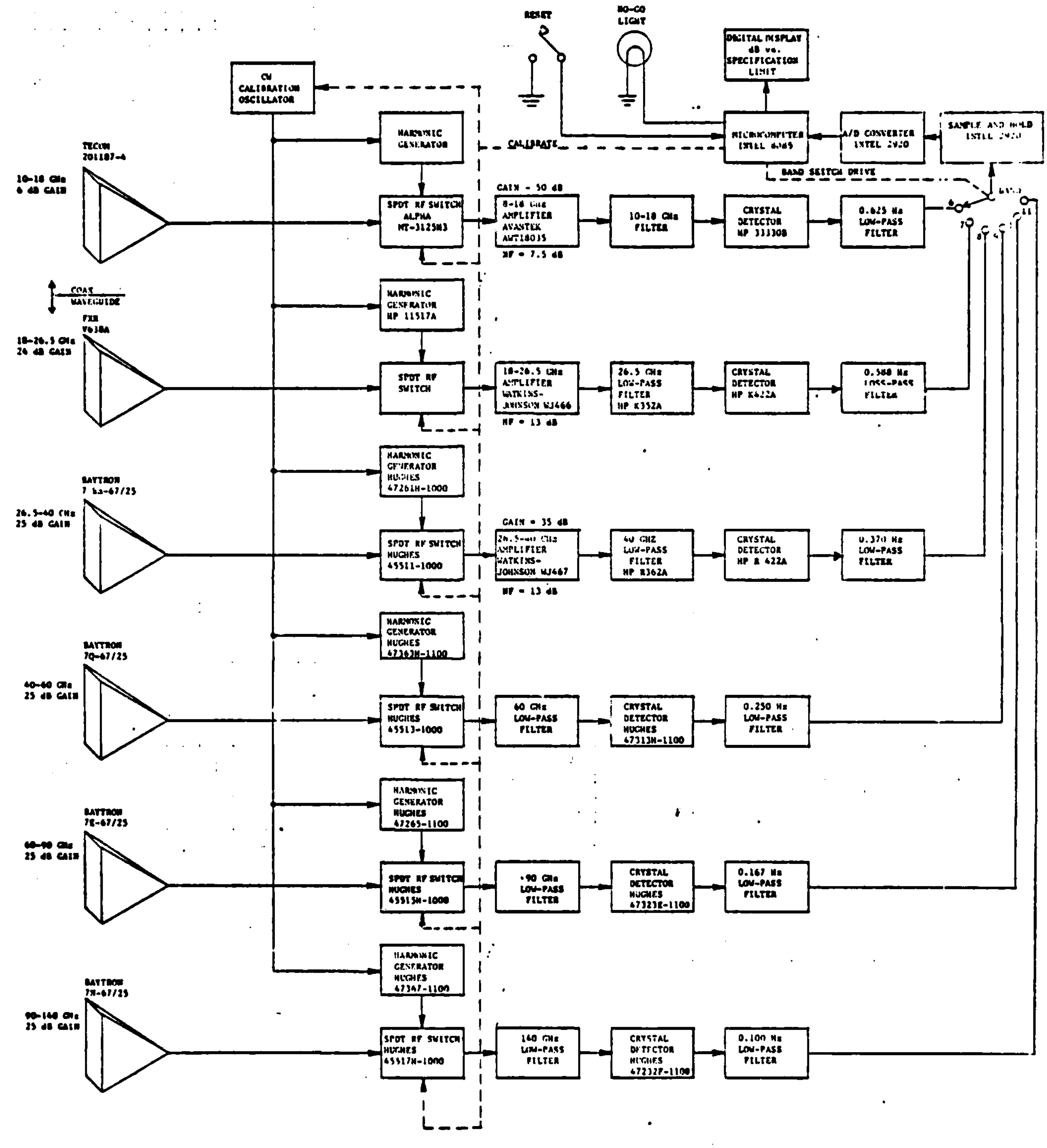

Figure 2 Broadband Measurement System Block Diagram 10-140 GHz Using Crystal Video Techniques.

System. The bandswitch in the High-Band System starts with Band 6, the first 5 bands being in the Low-Band System. The frequency range from 10 to 140 GHz is covered in 6 new bands.

Band 6, covering 10 to 18 Ghz, is determined by the 8 to 18 GHz bandwidth of available wideband solid-state preamplifiers. Interconnections in this band are coaxial, using OSM, or equivalent, connectors. Signals received by a horn antenna are passed through a coaxial calibration switch to the preamplifier which provides approximately 50 dB of gain at a noise figure of 7.5 dB. The output of the preamplifier is filtered to eliminate out-of-band responses (and amplifier noise), and passed to a crystal detector. The output of the detector is low-pass filtered, peak digitized, compared with the specification limit in the microcomputer, displayed in decibels relative to the specification limit and, if the level exceeds the limit, caused to illuminate the no-go light. A preliminary software flow diagram for the controlling microcomputer is shown in Appendix III.

Bands 7 through 11 are in waveguide and are determined by the waveguide passbands. Larger passbands would be available in ridged waveguide but only a very limited amount of off-the-shelf ridged-waveguide hardware is available, thus no attempt has been made to use it extensively here. Except for a few items, such as one of the waveguide switches (18 - 26.5 GHz) and some of the filters, all of the components shown in Figure 1 are catalog items. Operation of bands 7 through 11 is the same as described for Band 6, except that preamplifiers are not readily available for Bands 9, 10 and 11.

a) <u>Antennas</u>

The antennas used above 10 GHz are all waveguide horns. The 10 to 18 GHz horn is quad-ridged and has a coaxial output for full-band coverage. Polarization can be either linear or circular. The higher-frequency horns all have waveguide outputs and are linearly polarized.

Horn antennas have been selected because they are simple, rugged, provide high gain, and are readily available from several sources. The antennas above 18 GHz are so-called "standard-gain" horns in which performance is easily reproducible and fully calibrated. The 10 - 18 GHz horn can also be easily calibrated. Catalog data on the various antennas used in Figure 2 are shown in Table 1.

Detailed gain calibration curves for the antennas in Table 1 have not been obtained. However, the shapes of the gain curves are important in establishing the Broadband Measurement Specification because the slope of the new Specfication Limits must match the slope of the antenna factors if errors are to be kept within reasonable bounds. A set of typical gain calibration curves for Narda Microline horn antennas with nominal 15 dB gain between 8.2 and 40 GHz is shown in Figure 3. These have a uniform nominal slope closely approximating a 6 dB/octave gain increase with frequency. For comparison, a nominal 20 dB gain Scientific-Atlanta horn, for which data are shown in Figure 4, has gain slopes which vary from 6 dB/octave to 1 dB/octave across the band. By sacrificing some gain, horn antennas can be built with almost constant gain as has been described by P. R. Wickliffe of Bell Telephone Laboratories. A compromise factor of 3 dB/octave will be used when setting the slope of the new Specification Limits above 10 GHz.

b) <u>Coaxial and Waveguide Switches</u>

Full bandwidth switches are available in coax up to 18 GHz in solid-state and up to 26.5 GHz in mechanical versions. Insertion losses for solid state switches at 18 GHz run 2.1 dB while mechanical switches run 1.5 dB. Operating life for mechanical switches are rated in excess of 10^6 operations. Even so, solid-state switching is to be preferred for microprocessor control because they can be operated frequently without degradation.

Table 1. Antenna Characteristics, 10 - 140 GHz

Band	Frequency	Make	Model	Nominal Gain	Gain Variation	Size, Inches L	W	H	Weight
6	10-18 GHz	TECOM	201187-4	6 dB	3 dB	3.1	1.0	1.0	0.5 lbs
7	18-26.5	FXR	YG38A	24	1.7	10.7	3.0	4.0	1.5
8	26.5-40	BAYTRON	7Ka-67/25	25	2.0	6.5	2.4	2.8	0.8
9	40-60	BAYTRON	7Q-67-25	25	2.0	4.1	1.4	1.8	0.5
10	60-90	BAYTRON	7E-67/25	25	2.2	3.9	1.1	1.3	0.1
11	90-140	BAYTRON	7N-67/25	25	3.5	3.9	0.6	0.9	0.1

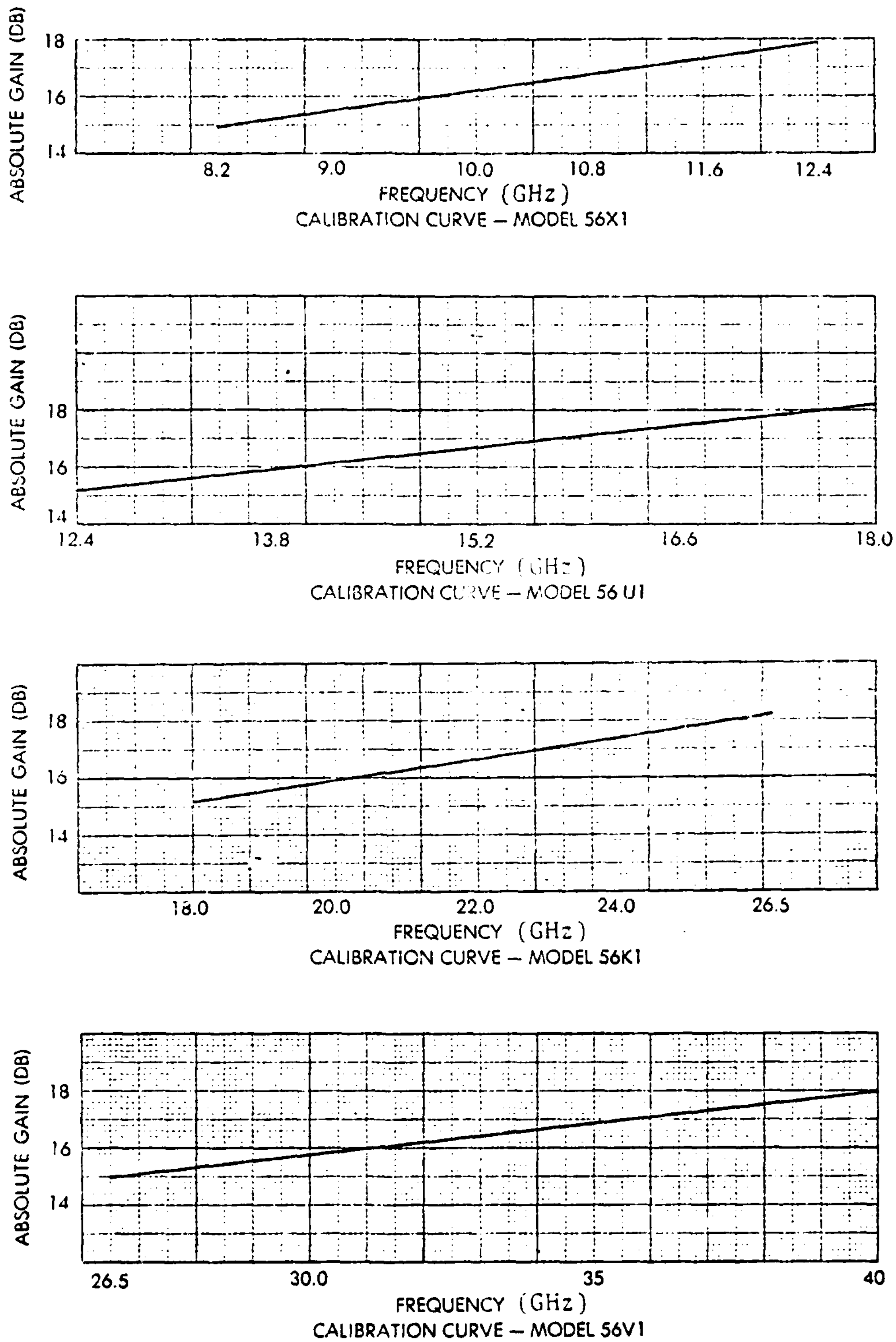

Figure 3. Narda Microline Horn Antenna Gain.

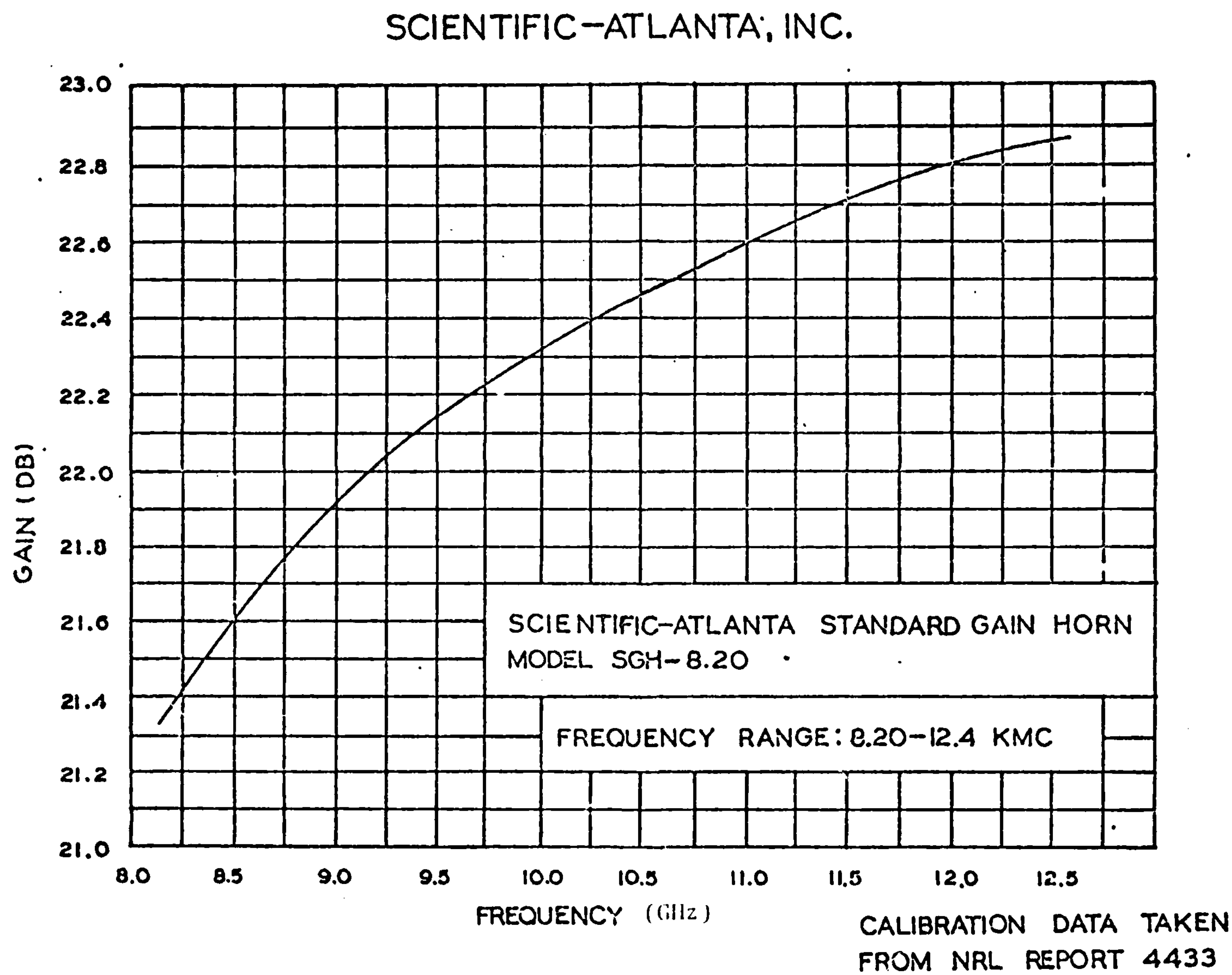

Figure 4. Scientific-Atlanta Horn Antenna Gain.

Solid-state switches above 18 GHz are apparently not available with full waveguide bandwidth; thus the switches will have to be mechanical. A catalog waveguide switch for the 18 to 26.5 GHz range has not been located, but an exhaustive search has not been made. Above 26.5 GHz, mechanical full bandwidth waveguide switches are available from several millimeter-wave houses. Insertion losses are on the order of 0.7 dB or less, and actuation time is on the order of 150 milliseconds.

c) Preamplifiers

Wideband solid-state preamplfiers are available from Avantek up to 18 GHz. An 8 to 18 GHz unit has been chosen for Band 6. Gains are available from 25 to 45 dB in 5 dB increments. Noise figures are 7.5 dB. Power output at the 1 dB compression point is +10 dBm and the intermodulation intercept point is 20 dBm. Gain flatness at 50 dB gain (two amplifiers with 25 dB gain) is ± 4 dB maximum, which may cause accuracy problems in a broadband system such as is being considered here.

Low-noise travelling wave tubes (TWT's) are available from Watkins-Johnson, and others, up to 40 GHz. For Band 7, the WJ466 would be the typical choice with 13 dB noise figure, 40 dB gain and 20 dBm output capability. For Band 8, the WJ467 would be typical with 15 dB noise figure, 35 dB gain and 10 dBm output capability. Lack of gain flatness could cause problems. The WJ466 is rated ± 2 dB and the WJ467 is rated ± 4 dB.(see Sect. B.2)

d) Crystal Detectors

Commercial Schottky-diode detectors have been chosen for the version of the hypothetical Broadband Measurement System using crystal-video techniques above 10 GHz. The bandwidths are so large that, even with specially designed detectors, there is little possibility of achieving sufficient dynamic range to handle impulses. Data on the selected detectors appear in Table 2.

Table 2. Schottky-Diode Detector Characteristics Above 10 GHz

Band	Frequency	Manufacturer	Model Number	Voltage Sensitivity	Frequency Response
6	10-18 GHz	Hewlett-Packard	33330B	0.5 mV/μW	±0.6 dB
7	18-26.5	Hewlett-Packard	K422A	0.3	±2.0
8	26.5-40	Hughes	47321H	0.1	±1.5
9	40-60	Hughes	47323H	0.1	±1.5
10	60-90	Hughes	47325H	0.075	±2.0
11	90-140	Hughes	47327H	0.075	NA

Video response characteristics are not specified. It is anticipated that the output bypass capacitors can be made part of the video low-pass filters required to control the broadband/narrowband response ratio. The required average detector characteristic is assumed to be achievable by simply making the video load resistance equal to, or less than, the detector diode video resistance. Full-wave detectors, although they would improve sensitivity, are not required in the High-Band System for bipolar detection because there is insufficient RF low-frequency response to support unipolar pulses, and either positive or negative polarity detectors will work equally well.

e) <u>Video Low-Pass Filters</u>

The video low-pass filters will be chosen to maintain a value for the wideband/narrowband response ratio, r, of 20 dB, the same as used in the Low-Band System. Using Equation (22) from the Second Quarterly Report:

$$B_0 \simeq 1/(2B_I r^2) \tag{1}$$

where B_0 is the video low-pass filter cutoff frequency and B_I is the RF input frequency, both in megahertz. For the various bands:

$$B_{0/6} = 1/[2(8x10^3)(10^2)] = 0.625 \text{ Hz}$$
$$B_{0/7} = 1/[2(8.5x10^3)(10^2)] = 0.588 \text{ Hz}$$
$$B_{0/8} = 1/[2(13.5x10^3)(10^2)] = 0.370 \text{ Hz}$$
$$B_{0/9} = 1/[2(20x10^3)(10^2)] = 0.250 \text{ Hz}$$
$$B_{0/10} = 1/[2(30x10^3(10^2)] = 0.167 \text{ Hz}$$
$$B_{0/11} = 1/[2(50x10^3)(10^2)] = 0.100 \text{ Hz}$$

These values are used for the video low-pass filters in Figure 1.

f) <u>Crystal-Video Receiver Sensitivity</u>

The narrowband (CW) sensitivity for Bands 6, 7 and 8 can be found using Equation (11) from the Third Quarterly Report:

$$V_{SI} = -0.4 + F_I + 5 \log_{10}(2B_0B_I - B_0^2) \text{ dB}\mu\text{V} \qquad (2)$$

where V_{SI} is the threshold RMS signal input in dBμV for peak signal equal peak noise in the output, F_I is the RF noise figure in dB, B_I is the RF bandwidth in MHz and B_0 is the video bandwidth in MHz. Throughout these and the following calculations, the presence of waveguide in the system is ignored as far as units are concerned, and units are standardized in terms of dBμV across 50 ohms for simplicity.

Assuming that the RF amplifier has sufficient gain so that the system is input noise limited, the CW sensitivity for Band 6 is

$$\begin{aligned} V_{SI} &= -0.4 + 7.5 + 5 \log_{10}[2(0.625 \times 10^{-6})(8 \times 10^{3}) \\ &\quad -(0.625 \times 10^{-6})^{2}] \\ &= -0.4 + 7.5 - 10.0 \\ &= -2.9 \text{ dB}\mu\text{V} \end{aligned}$$

The corresponding CW sensitivity for Band 7 is 2.6 dBμV and for Band 8 is 4.6 dBμV.

The minimum RF amplifier gain, G, necessary for the system to be input noise limited will be determined as

$$G = T_{SS} - V_{SI} \qquad (3)$$

where T_{SS} is the tangential sensitivity of the detector. (Equation (3) is resonably consistant with Equation (10) in the Second Quarterly Report.) Using Equation (7) from the Third Quarterly Report, the tangential sensitivity of the diode detector is

$$T_{SS} = 12.1 + 5 \log_{10} B_0 + 5 \log_{10} \left[\frac{R_V{}^2 F_0}{R_0} + R_V t_d \right]$$

$$-10 \log_{10} \gamma + C_f \ \text{dB}\mu\text{V} \qquad (4)$$

where R_V is the detector diode video resistance in ohms, F_0 is the video amplifier noise figure in ratio, R_0 is the video load resistance in ohms, t_d is the diode noise temperature ratio, γ is the diode voltage sensitivity in mV/μW and C_f is a frequency correction factor in dB. The diode noise temperature ratio can be obtained using Equation (9) from the Third Quarterly Report as:

$$t_d = B_0 + f_N \ln \left[\frac{B_0}{f_L} + 1 \right] \qquad (5)$$

where f_N is the diode flicker noise corner frequency in hertz and f_L is the lower cutoff frequency for the video bandwidth, B_0, in the same units as B_0. Unfortunately, Equation (5) is indeterminate for a DC-coupled detector ($f_L = 0$), and the arbitrary assumption of $f_L = 1$ Hz used in the Third Quarterly Report is not appropriate because B_0 is less than 1 hz. An equally arbitrary assumption that negligible noise is contributed below $f_L = 0.1\ B_0$ permits evaluation of Equation (5) for Bands 6 through 11 as:

$$t_d = 0.625 + (3 \times 10^3) \ln \left[\frac{0.625}{0.0625} + 1 \right]$$

$$= 0.625 + (3 \times 10^3)\ (2.40)$$

$$= 7194$$

where f_N has been assumed to have a typical value of 3 kHz for a Schottky diode.[1] Substituting this value into Equation (4), along with typical assumed value of :

R_V = 1500 ohms

F_0 = 2(a 6 dB video noise figure),

R_0 = 50 ohms,

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[1] Hewlett-Packard "Hot Carrier Diode Video Detectors," Application Note 923, page 4.

and $\gamma = 0.5$ from Table 2, the tangential sensitivity for Band 6 is:

$$T_{SS} = 12.1 + 5\log_{10} 0.625 + 5\log_{10}\left[\frac{1500^2(2)}{50} + 1500(7194)\right] - 10\log_{10} 0.5 + 0$$
$$= 12.1 - 1.0 + 35.2 + 3 + 0$$
$$= 49.3 \text{ dB}\mu\text{V}$$

and the minimum gain required can be calculated using Equation (3) as:

$$G = 49.3 + 2.9$$
$$= 52.2 \text{ dB}$$

which was rounded off to 50 dB when used in Figure 2.

Values of V_{SI}, T_{SS} and other factors necessary for calculation of system sensitivity are listed in Table 3 for Bands 6 through 11. The Antenna Gains were obtained from Table 1. with the nominal gain assumed at the lower band edge and gain increasing at the rate of 3 dB/octave. Antenna Factors, F_A, were obtained from the Antenna Gains, G_A, using the equation:

$$F_A = 20\log_{10} f_{(MHz)} - G_A - 29.7 \text{ dB/m.} \qquad (6)$$

For the Band 6 lower edge,

$$F_A = 20\log_{10} 10^4 - 6.0 - 29.7$$
$$= 80 - 6.0 - 29.7$$
$$= 44.3 \text{ dB/m}$$

Detector Voltage Sensitivity, γ, was obtained from Table 2. RF Amplifier Gains and Noise Figures were taken from Figure 2. Conducted Sensitivity was calculated as $T_{SS}-G_A$ using Equation (3). Radiated Sensitivities were obtained by adding the Antenna Factors to the Conducted Sensitivities.

Both the Conducted Sensitivity and Radiated Sensitivity listed in Table 3 are at least partially detector noise limited on all bands. This means that the sensitivity could be improved by using more RF amplifier gain in Bands 6, 7 and 8 where RF amplifiers are available but, as will be seen later when

Table 3. Sensitivity Using Crystal-Video Techniques Between 10 and 140 GHz.

Band	Frequency	Antenna Gain	Antenna Factor	Detector Voltage Sensitivity, γ	Detector Tangential Sensitivity, T_{SS}	RF Amp Noise Figure, F_I	RF Amp Gain, G	Input Noise Limited Sensitivity, V_{SI}	Conducted Sensitivity	Radiated Sensitivity
6	10 GHz	6.0 dB	44.3dB/m	0.5 mV/μW	49.3 dBμV	7.5 dB	50 dB	-2.9 dBμV	-0.7 dBμV	43.6 dBμV/m
	18	9.0	46.4							45.7
7	18	24.0	31.4	0.3	51.7	13	40	2.6	11.7	43.1
	26.5	25.7	33.1							44.8
8	26.5	25.0	33.8	0.3	52.7	15	35	4.6	17.7	51.5
	40	27.0	35.3							53.0
9	40	25.0	37.3	0.1	58.3	NA*	None	Detector Limited	58.3	95.6
	60	27.0	38.9							97.2
10	60	25.0	40.9	0.075	60.4	NA*	None	Detector Limited	60.4	101.3
	90	27.2	42.2							102.6
11	90	25.0	44.4	0.075	61.5	NA*	None	Detector Limited	61.5	105.9
	140	28.5	44.7							106.2

* RF amplifiers are not available for this band.

hypothetical broadband measurement specification limits are considered, sensitivity in these bands is already more than adequate for realistic measurements. It is Bands 9, 10 and 11, where RF amplifiers are not available, that need more sensitivity. Improved sensitivity can be obtained by using an alternate approach in which mixers are used to convert High-Band frequencies down to Low-Band frequencies where they can be processed by the hypothetical Broadband Measurement System previously developed in the Second and Third Quarterly Reports.

2) Fundamental Mixing Above 10 GHz

Fundamental mixing refers to a frequency conversion where the mixer product frequencies of interest are the sum and difference between the frequency of an input signal and the fundamental frequency of the local oscillator. Harmonic mixing, where the input signal mixes with harmonics of the local oscillator generated in the mixer, has been used for years in spectrum analyzers and other receivers applicable to EMI measurements above 10 GHz, but does not produce good sensitivity. For example, Hughes recently marketed their 4734-series Spectrum Analyzer Mixers for extending the frequency range of the Hewlett-Packard spectrum analyzers up to 110 GHz. The advertised conducted sensitivities are 47 dBμV in Band 8 (26.5 - 40 GHz), 53 dBμV in Band 9 (40 - 60 GHz), 63 dBμV in Band 10 (60 - 90 GHz) and 67 dBμV up to 110 GHz in Band 11. Comparing these values with the conducted sensitivites for the crystal-video technique in Table 3 does not show much improvement. This is because the Hewlett-Packard spectrum analyzer local oscillator frequency is in the 2 to 4 GHz range and the mixer must be operated at the 25th harmonic to tune to 100 GHz. In general, the higher the harmonic, the lower the local oscillator power available. Thus harmonic mixer conversion loss increases rapidly with harmonic number and sensitivity deteriorates accordingly. Achievement of adequate sensitivity requires the use of fundamental or low-harmonic mixing.

a) <u>Hardware for Fundamental Mixing Above 10 GHz</u>

A hypothetical Broadband Measurement System using fundamental mixing between 10 and 110 GHz is shown in Figure 5. Extension of coverage to 140 GHz can be obtained, with little loss in sensitivity, by using 2nd harmonic mixing and slightly different hardware in Band 11. Only lack of a suitable local oscillator prevents operation to 140 GHz in the system shown.

The antennas, calibration switches and low-pass filters which preceed the mixers are the same as for the Crystal Video Broadband Measurement System shown previously in Figure 2. The Band 6 mixer is double-balanced so that local oscillator noise feedthrough is minimized. The mixers in Bands 7 through 11 are single-ended so that local oscillator energy must be coupled into the input along with the signal by using a directional coupler or similar device. The noise introduced along with the local oscillator signal in Bands 7 through 11 is not attenuated and may cause sensitivity problems.

The local oscillators are sweepers, which are the only wideband sources available above 40 GHz. This is fortunate because sweepers are readily controllable by the microcomputer. The frequency ranges shown for the sweepers are adequate to insure that a fundamental mix product will be generated in Band 3 (1 - 4 GHz) of the Low-Band System for any signal within a given high band. Since broadband measurements are the objective, the frequencies are not critical and may be stepped in 3 GHz or smaller increments, or continuously swept. (Translation to Band 2 (0.1 - 1 GHz) would have some advantages but a gap in local oscillator (Hewlett-Packard 8620 Sweeper) coverage between 22 and 26.5 GHz complicates system realization. The gap could be avoided by use of Wiltron 610 series sweepers below 40 GHz, but the Hewlett-Packard main frame is needed for the Hughes heads above 40 GHz. and providing both would be more expensive.

b) Sensitivity Using Fundamental Mixing

The mixer conversion losses for Bands 6 through 11 are shown in Table 4, along with the other system data necessary for computing the sensitivity achievable with the fundamental mixing approach. Conducted Sensitivity, V_{SI}, was calculated using Equation (2) with the RF noise figure, F_I, determined as (Mixer Conversion Loss in dB) + (IF Noise Figure in dB).[2] Assuming that the 1 - 4 GHz IF Preamplifier in Figure 4 has sufficient gain, the IF Noise Figure is the 6.5 dB noise figure of the preamplifier, and for Band 6:

$$
\begin{aligned}
V_{SI} &= -0.4 + (9.5 + 6.5) + 5 \log_{10} \left[2(1.7 \times 10^{-6})(3 \times 10^{3}) - (1.7 \times 10^{-6})^2 \right] \\
&= -0.4 + 16.0 - 10.0 \\
&= 5.6 \text{ dB}\mu\text{V}
\end{aligned}
$$

where the video bandwidth B_0 = 1.7 Hz and the RF bandwidth B_I = 3 GHz for Band 3 of the hypothetical Broadband Measurement System (Low-Band System) described in the Second and Third Quarterly Reports. Radiated Sensitivity was calculated by adding the Antenna Factor to the Conducted Sensitivity. Except in Band 6, where the 7.5 dB noise figure of the preamplifier used in the crystal-video approach is hard to beat, the sensitivities with fundamental mixing in Table 4 are a considerable improvement over those obtained with the crystal-video techniques in Table 3.

3) Hypothetical Broadband Measurement Specification Extended to 100 GHz

Figure 6 of the Second Quarterly Report, Hypothetical Broadband Measurement Specification, First Cut, has been extended to 100 GHz in Figure 5.

The slope of the Hypothetical New Narrowband Limit and Hypothetical New Broadband Limit curves between 10 GHz and 100 GHz is 3 dB/octave. This slope was determined by reducing the

[2] This neglects mixer and local oscillator noise contributions which may be significant, particularly with single-ended mixers.

Table 4. Sensitivity Using Fundamental Mixing Between 10 and 140 GHz

Band	Frequency	Ant. Gain, G_A	Ant.Factor, F_A	Mixer Conversion Loss	Conducted* Sensitivity	Threshold CW Field Strength
6	10 GHz	6.0 dB	44.3 dB/m	9.5 dB	5.6 dBμV	49.9 dBμV/m
	18	9.0	46.4			52.0
7	18	24.0	31.4	9.5	5.6	37.0
	26.5	25.7	33.1			38.7
8	26.5	25	33.8	9.5	5.6	39.4
	40	27.0	35.3			39.9
9	40	25	37.3	10.5	6.6	43.9
	60	27.0	38.9			45.5
10	60	25	40.9	11.5	7.6	48.5
	90	27.2	42.2			49.8
11	90	25	44.4	13.5	9.6	54.0
	140**	28.5	44.7			54.3

* Assuming 6.5 dB IF Noise Figure

** Assuming Availability of a Local Oscillator Above 110 GHz. (Harmonic mixing cannot be used with the Band 11 mixer assumed here because the required local oscillator frequencies are below waveguide cutoff.)

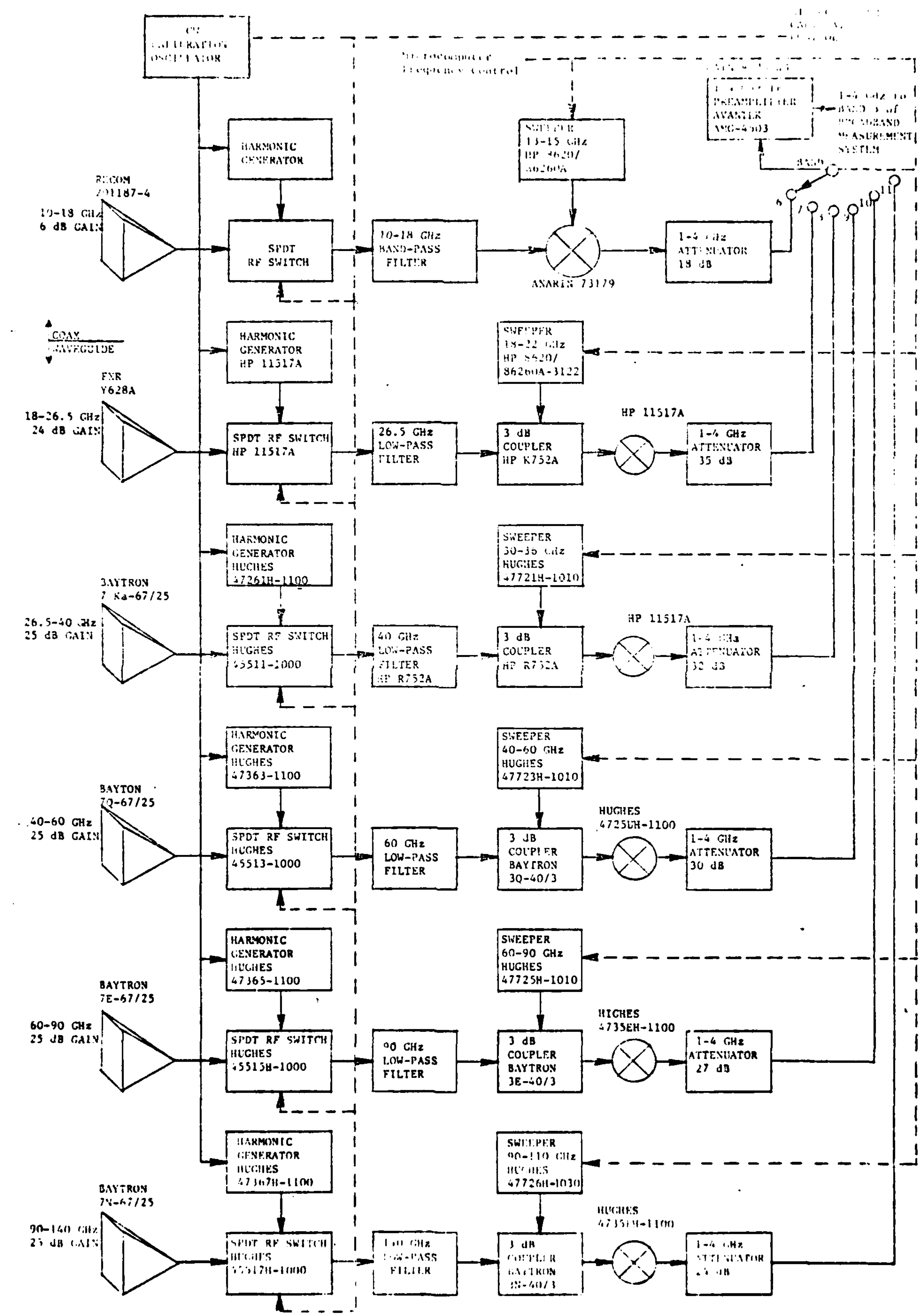


Figure 5. Broadband Measurement System Block Diagram, 10-110 GHz Using Fundamental Mixing

6 dB/octave slope of the antenna factors for constant-gain antennas (antenna factor increses directly with frequency for a constant-gain antenna) and the flat antenna factors of some horn antennas, such as those shown in Figure 2. The 3 dB/octave compromise slope closely matches the increase of gain with frequency found in many typical waveguide horn antennas (see Section A.1.a). The Limit curves resulting are essentially parallel to the sensitivity curves for the hypothetical Broadband Measurement System, thereby minimizing measurement errors due to antenna gain variations.

The sensitivites obtainable with the hypothetical Broadband Measurement System above 10 GHz using both the crystal-video technique (solid-line segments) and fundamental mixing (short dashes) are plotted on Figure 6 for comparison with the new limits. Either technique can provide adequate sensitivity up to 40 GHz. However, above 40 GHz, the non-availability of RF amplifiers makes the cyrstal-video technique impractical, while frequency conversion using fundamental (or low-harmonic) mixing can provide more than adequate sensitivity.

The hypothetical Broadband Measurement Specification can be extended downward in frequency to 60 Hz without running into severe hardware implimentation limitations. The new limit curves would be horizontal extensions of those shown in Figure 6. The hypothetical Broadband Measurement System in Figure 3 of the Third Quarterly Report (p. 26) would have to be modified by extending the low-frequency response of the preamplifier down to 60 Hz and reducing the lower cutoff frequency of the input band-pass filter to 60 Hz to accommodate the lower frequencies. Other RF components, such as the antenna (response down to 20 Hz) and the crystal detector (response down to dc), already have adequate frequency response. Presence of the 50 Hz video low-pass filter precludes extension much below 60 Hz, although the problems of RF feedthrough into the video that would result may not be significant.

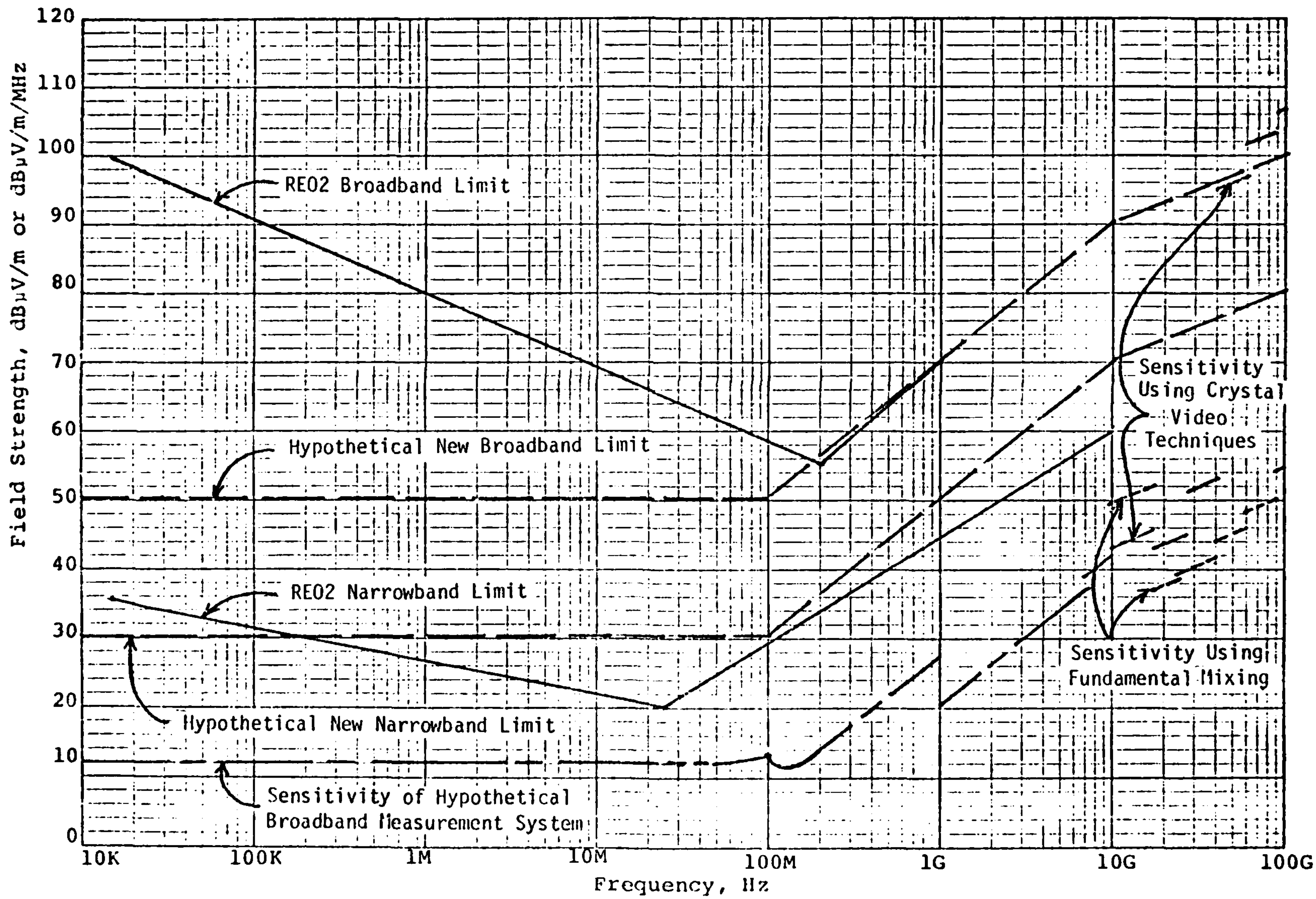


Figure 6 Hypothetical Broadband Measurement Specifcation Extended to 100 GHz

a) Dynamic Range Above 10 GHz

The system using fundamental mixing in Figure 4 will be assumed for dynamic range calculations. Antenna output levels for narrowband signals at the hypothetical New Measurement Specification Limits of Figure 6 are shown in Table 5. The antenna outputs at the new specification limits are at least 20 dB greater than the conducted Sensitivities shown in Table 4, therefore maximum dynamic range will be obtained with reduced gain to achieve detector-limited sensitivity rather than with input-noise-limited sensitivity, the same as for the Low-Band (Bands 1 through 5) System described in the Third Quarterly Report.

The dynamic range calculations are summarized in Table 6. The object is to translate frequencies in Bands 6 through 11 (High Bands) to Band 3 of the Low-Band System (Figure 3 of the Third Quarterly Report) without compromising the Band 3 dynamic range. This ideal can be achieved for narrowband signals, but not for impulses because the RF bandwidth is wider in the high bands than in Band 3, as was discussed on Page 24 of the third Quarterly Report.

Calculation of dynamic range starts with the Specification Limit CW Antenna Outputs from Table 5. These are decreased by the Mixer Conversion Loss (rounded off from Table 4) and increased by the IF Amplifier Gain to obtain the Specification Limit Band 3 Input Without Attenuation, which is the level which would appear at the Band 3 input if no attenuation was inserted. In every case, the resulting levels are in excess of the 23 dBμV Band 3 Threshold Sensitivity obtained from the Specification Limit CW Antenna Output figures in Table 5 of the Third Quarterly Report, indicating that the IF amplifier gain is adequate.

The Overall Attenuation Required to make input signals just equal to the threshold is next calculated by subtracting 23 dBμV from the Specification Limit Band 3 Input Without

Table 5. CW Antenna Aoutput At Hypothetical New Specification Limit

Band	Frequency	Narrowband Spec. Limit Field Strenght	Antenna Factor	CW Ant. Output
6	10 GHz	70 dBμV/m	44 dB/m	26 dBμV
	18	72	47	25
7	18	72	31	41
	26.5	74	33	41
8	26.5	74	34	40
	40	76	36	40
9	40	76	37	39
	60	78	39	39
10	60	78	41	37
	90	80	43	37
11	90	80	44	36
	100	80	44	36

Table 6. Dynamic Range

Band	Spec.Limit CW Ant.Out	Mixer Conv.Loss	IF Amp Gain	Spec Limit Band 3 Input WO Atten	Band 3 Threshold Sensitivity	Overall Atten. Required	LO Drive Available	Amplified Mixer Output	IF Amp Output	Band 3 Input
6	26 dBμV	10 dB	25 dB	41 dBμV	23 dBμV	18 dB	117 dBμV	122 dBμV	114dB V	106dBμV
7	41	10	25	56	23	35	117	122	114	106
8	40	10	25	55	23	32	117	122	114	106
9	39	11	25	53	23	30	109	112	114	106
10	37	12	25	50	23	27	109	110	114	106
11	36	14	25	47	23	24	109	106	114	106

Band	Frequency	Spec. Limit Imp.Ant.Out	$20 \log_{10}$ RF BW	Spec Limit Band 3 Input		RF Atten. Required	Dynamic Range Using RF & IF Attenuation		Dynamic Range Using IF Atten. Only	
				CW	Impulse		CW	Impulse	CW	Impulse
6	10-18 GHz	46 dBμV/MHz	78 dB	23 dBuV	121 dBμV	2 dB	83 dB	-15 dB	81 dB	-17 dB
7	18-26.5	62	79	23	122	17	83	-16	66	-33
8	26.5-40	60	83	23	126	16	83	-20	67	-36
9	40-60	59	86	23	129	24	83	-23	59	-37
10	60-90	57	90	23	133	23	83	-27	60	-50
11	90-140	56	94	23	137	24	83	-31	59	-55

Attenuation. This attentuation can be all placed between the antennas and the mixers (RF attentuation) with the possibility of excessive noise figure degradation, or part of the attenuation can be placed after the mixer (IF attenuation) to reduce effects on noise figure. Placing all of the attenuation after the mixer, which would be ideal from the hardware standpoint of not requiring waveguide attenuators, reduces dynamic range as will be seen later.

Attenuation will be optimally apportioned in the system when no component overloads before another. Overload can occur in the mixers, in the IF amplifiers and at the Band 3 input. From Table 5 of the Third Quarterly Report, Band 3 has an 83 dB CW dynamic range which, with the 23 dBμV sensitivity, places the overload point at 23 + 83 = 106 dBμV. The IF amplifier has a +7 dBm output capability (1 dB compression), placing its overload point at 114 dBμV. The mixers have input overload points which will be approximately equal to the local oscillator (LO) drive level less the conversion loss.[3] The mixer overload points are referred to the Band 3 input, for easy comparison with the other overload points in Table 6, by subtracting out twice the conversion losses (once to obtain the saturated input level and a second time to obtain the saturated output level) and adding in the IF amplifier gain. The resulting amplified Mixer Output Overload Point is the Band 3 input that would exist at mixer saturation if the amplifier were able to handle the power (The IF amplifier will not have to because attentuation is going to be added.)

If RF attentuation is allowed, CW dynamic range is equal to the Band 3 Threshold Sensitivity (23 dBμV) minus whichever of the Overload Points is the lowest. In every case, the Band 3 input (106 dBμV) is the lowest and we have succeeded in achieving our goal of not compromising the Band 3 dynamic range. The Amplified Mixer Output Overload Point for Band 11 just equals the Band 3 Input Overload Point which justifies the choise of IF amplifier gain. The actual attenuation which must be assigned

[3]Anaren Catalog M9001-67, 5/78 Revision, page 165.

to the RF side of the system to achieve full dynamic range is tabulated under RF Attenuation Required, and is calculated as the CW Dynamic Range Using RF Attenuation (83 dB) plus the Specification Limit Band 3 Input Without Attenuation minus the Amplified Mixer Output Overload Point, under the assumption that early mixer saturation can only be prevented by RF attenuation. (Some RF attenuation can be provided economically by reducing antenna gain.)

If RF attenuation is not allowed, the CW dynamic range can be calculated as the Amplified Mixer Output Overload Point minus the Specification Limit Band 3 Input Without Attenuation, because the mixer overloads first. As can be seen, the figures are heavily degraded relative to the figures with RF attenuation, particularly in the upper bands.

Impulse dynamic ranges were calculated assuming a Broadband/Narrowband Response Ratio, r, of 20 dB, as was done in the Second and Third Quarterly Reports. This means that the Specification Limit Impulse Antenna Output is 20 dB greater in terms of dBμV/MHz than the equivalent CW level in dBμV. The CW levels must be futher increased by 20 $\log_{10}$ of the RF bandwidth to get the Specification Limit Band 3 Input levels for impulses because peak impulse voltage is directly proportional to bandwidth.

As was the case in Bands 3,4 and 5 of the Low-Band System, the Band 6 through 11 Impulse Dynamic Ranges are all negative. The RF bandwidths are simply too large to pass a true, worst-case impulse without saturation occuring before detection. However, the System is capable of handling broadband signals having up to 1 GHz coherent bandwidth from Band 3 up, so there is no real deterrent to including a broadband limit in any new Broadband Measurement Specification. The comments on page 24 of the Third Quarterly Report for the Low-Band System also apply to the High-Band System.

B. <u>Accuracy of Hypothetical Broadband Measurement System</u>

The philosophy used in developing the hypothetical Broadband Measurement System has been to design for flat frequency response to conducted signals and then to convert from conducted to radiated signals by using antenna factors which follow easily achievable antenna response laws. Thus the hypothetical new Broadband Measurement Specification limits for radiated signals take on the shape of the antenna response laws. Once the limits are set, any failure of the System to achieve flat frequency response to conducted signals, or to follow the proper antenna response law for radiated signals, will result in measurement errors.

In any measurement system there are residual errors that remain after the primary variations have been calibrated out. The residual errors that have been identified as remaining in the hypothetical Broadband Measurement System after calibration are shown in Table 7. Some errors, such as those due to waveguide losses, are due to factors which cause sensitivity to improve with frequency. These are given a + sign in Table 7. Conversely, some factors, such as cable losses, cause sensitivity to degrade with frequency and are given a - sign. Most factors are random with frequency and are not given a sign.

For a worst-case analysis, the unsigned (random) errors are added together and summed with the residual of the signed errors, disregarding the sign of the residual. Thus a negative error cancels a positive error or vice versa, but the difference adds to the sum of the unsigned errors.

Most errors are inherent in specific components and are relatively unaffected by the way the system is set up. However, errors due to transmission losses are dependent on the amount of cable or waveguide used in a particular setup, and typical lengths of 10 feet for cable and one foot for waveguide have been assumed in Table 7. Errors due to the measurement environment, such as standing waves and directional effects, have not been considered in this Section.

The various errors listed in Table 7 will be discussed in the following Subsections.

Table 7. Residual Errors In Hypothetical Broadband Measurement System.

Band	1	2	3	4	5	6	7	8	9	10	11
	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)
Antenna	-2	+6	-1	-0.2	0	+0.4	0	+0.2	+0.5	+0.4	+1.6
RF Amplifier	0	1	1	1	1						
Detector	0	0	0.1	0.1	0.1						
Mixer						3	3	3	3	4	4
IF Amplifier						2	2	2	2	2	2
RF & IF Cable*	-0.2	-0.6	-1.1	-0.8	-0.7	-1.5	-1.1	-1.1	-1.1	-1.1	-1.1
Input Waveguide**	—	—	—	—	—	—	0	+0.1	+0.1	+0.2	+0.5
Total, dB	-2.2	+6.4	-3.2	-2.1	-1.8	-6.1	-6.1	-5.8	-5.5	-6.5	+7.0

* Assuming 10' of Stripflex SF-304 (Time Wire & Cable) Between Antenna and Detector, or IF Output and Detector.

** Assuming 1' of Rectangular Waveguide Between Antenna and Mixer.

1) Antenna Errors

The major antenna error, +6 dB in Band 2, was noted previously in the Second Quarterly Report. The error is caused by a drop in the low-end gain of the particular antenna selected for the System within the narrow frequency range from 100 to 150 MHz. The problem is that complete coverage of the decade range from 100 to 1000 MHz with constant gain in one antenna is difficult to do. The antenna selected comes so close that its use, as opposed to breaking Band 2 into two bands with a better antenna between 100 and 150 MHz, is deemed appropriate to the broadband measurement concept. A gain equalizer, in which a 6 dB attenuator is bypassed below 150 MHz by a low-pass filter, can be added to correct the problem. There is sufficient sensitivity margin in the System to accept the loss introduced by such an equalizer and still make measurements to the new specification limits. The picture may also improve with future, or existing alternate, antenna developments.

For Band 1, there is a 2 dB rise in the high-end antenna factor, probably because the antenna is approaching resonance. This is within the ±2 dB accuracy desired for the System. Subsequent information about the particular antenna chosen indicates that a shorter rod, and therefore a higher antenna factor across the band, may have to be accepted to insure the flat frequency response assumed. There is sufficient sensitivity margin in the System to accommodate a considerable increase in antenna factor as long as it is flat across the band.

Bands 3, 4 and 5 all share the same broadband antenna. Detailed analysis of the manufacturer's calibration data (1 GHz increments) indicates a 1 dB increase in antenna gain (a 13 dB increase in antenna factor) with frequency over the two octaves of Band 3. Gain increases only 0.2 dB in Band 4 and essentially 0 dB in Band 5.

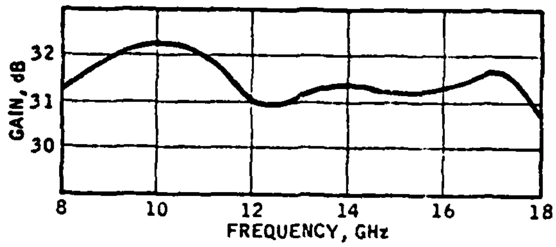
Waveguide horn antennas are used in Bands 6 through 11. As discussed in Section A.1.a, the gain of horn antennas typically increases at the rate of 3 dB/octave (or 10 dB/decade) across the waveguide bandwidth. The error figures in Table 7 were calculated by taking the manufacturer's published gain variation figures in dB from Table 1 and subtracting 10 $\log_{10}(f_U/f_L)$, where f_U is the upper band edge frequency and f_L is the lower band edge frequency, to obtain the variation from the new Specification Limits which assume 10 dB/decade variation. The errors are quite small.

2) RF Amplifier Errors

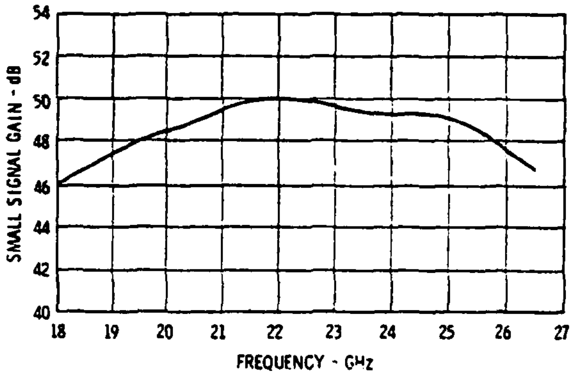
Broadband RF amplifiers are used in Bands 1 through 5. The gain variations, while small, are random with frequency depending on the equalization in a particular amplifier. The gain errors shown in Table 7 are all less than the nominal maximum values quoted by the manufacturers ($\pm$ 1 dB) and listed in tables elsewhere in these reports because the typical specific gain curves published by the same manufacturer show less typical error. For example, the gain curve for the Band 1 amplfier is shown to be absolutely flat over the frequency range of interest on a curve for which the ordinates have 0.1 dB resolution. The gain variations in the other RF amplifiers, while more significant, are quite acceptable.

If RF amplifiers, which are available up to 40 GHz, had been used above 10 GHz, the errors would have been greater. Some typical gain curves for amplifiers in this range are shown in Figure 7. The need for RF amplifiers above 10 GHz has been avoided without significant loss of sensitivity in the System by using frequency conversion with mixers driven by local-oscillators operating on fundamental or low-harmonic frequencies.

TYPICAL PERFORMANCE: AVANTEK AWT-18016 SOLID-STATE AMPLIFIER



TYPICAL PERFORMANCE: WATKINS-JOHNSON WJ-466 TWT



TYPICAL PERFORMANCE: WATKINS-JOHNSON WJ-467 TWT

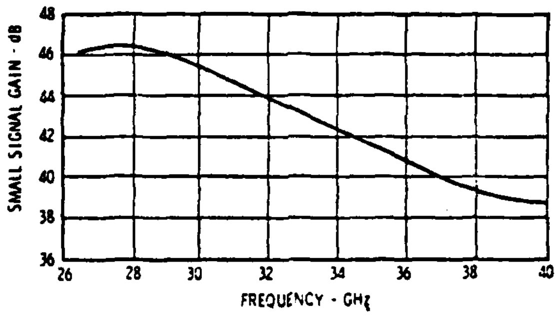


Figure 7. Gain Variations in Typical 10 to 40 GHz RF Amplifiers.

3) Detector Errors

Any lack of sensitivity flatness in the detectors used with the crystal-video approach will show up directly as a measurement error unless there are compensating errors. As with RF amplifiers, response variations in detectors are random depending on the individual detector characteristics. Detector response variations can often be reduced by use of padding attenuators or isolators. The variations assumed in Table 7 are taken from a typical curve for the Hewlett-Packard 33330C detector which is rated $\pm$0.6 dB to 18 GHz.

4) Mixer Errors

Mixer errors have proven hard to evaluate without experimental measurements. The Anaren 73129 mixer used in Band 6 has a rated voltage-standing-wave ratio (VSWR) of 2.9 which indicates probable amplitude ripple of approximately 3 dB peak-to-peak. The Hewlett-Packard 11517A mixer used in Bands 7 and 8 has a $\pm$3 dB rating over any 1 GHz frequency segment when used as a high-harmonic mixer for their spectrum analyzer, but a smaller 3 dB total variation has been assumed for operation as a fundamental mixer. Hughes was unable to provide any definitive data on their 4735-series broadband mixers used in Bands 9 through 11, but their catalog shows a $\pm$1.65 dB response variation up to 60 GHz and $\pm$2.0 dB up to 110 GHz when used as detectors, which should be indicative of the order-of-magnitude. The maximum rated VSWR of 2 for the Hughes mixers is not incompatable with these figures.

5) IF Amplifier Errors

The IF amplifier errors are essentially the errors in the Band 3 RF amplifier doubled because the gain is doubled (25 dB in both the Low-Band and High-Band portions of the System). The errors are the same for Bands 6 through 11 because the IF amplifier is common to all.

6) RF and IF Cable Errors

Any cable used at RF or IF in the System will tend to introduce errors because cable losses invariably increase with frequency. Cable losses are particularly significant in a Broadband Measurement System where each band is likely to cover several octaves, because the change in cable loss from one end of a band to the other is likely to be considerable and there is no easy way to compensate. Further, the magnitude of the losses involved are dependent on the actual type of cable used and the length incorporated into the setups. For the purposes of Table 7, 10 feet of cable has been assumed to be adequate, and a somewhat special 0.29-inch-diameter, teflon-insulated, foil-strip-shielded cable rated for use to 18 GHz has been assumed. Coaxial components are used at RF up to 18 GHz in the System, and at IF from 18 to 140 GHz. The effect of IF cable losses can be minimized by sweeping the local oscillator in such a way that all signals get to occupy the most sensitive part of the IF passband. Cable losses at IF tend to compensate for waveguide losses, which decrease with frequency.

7) Waveguide Errors

Unlike cable losses, waveguide losses invariably decrease with frequency across the waveguide bandwidth. One foot of silver-plated waveguide was assumed to be used in the System setups for Table 7. As frequencies approach 100 GHz, even this short length becomes significant.

8) Error Summation

The errors listed in Table 7 are summed for each band under the worst-case assumption that negative errors can cancel positive erros to obtain a signed residual, and that the residual is added to the unsigned errors with the total assuming the sign of the residual. Thus while the sign of the total is indicative of the general trend, only a small portion of the total may actually follow the trend.

The total errors in Bands 1, 3, 4, and 5 are all within the ±2 dB design goal set for the System. Band 2 can be brought within the design goal by addition of well-defined frequency compensation. All bands would fit within a ±4 dB error margin if cable and waveguide lengths are not unduely changed from those assumed.

The errors in Bands 8 through 11 can be compensated to well within ±2 dB by using tunable gain equalizers similar to the Series MMGE made by Frequency Engineering Laboratories of Farmingdale, N.J. Units are available with any number of channels, each tunable over a 500 MHz range and adjustable for 0 to 20 dB insertion loss. Units for lower frequencies are probably available from other sources. There is adequate sensitivity margin in the System to accommodate lossy equalizers.

C. Extrapolation of Measurement Distances

EMI radiated emission measurements made under an Intrasystem Electromagnetic Characteristics Requirement (APPENDIX I) will be made in a shielded enclosure at a distance of 1 meter (m), the same as presently required under MIL-STD-461. To apply the data to real-life situations where separation distances between emitter and receptor equipments are seldom exactly 1 meter, a means for extrapolation must be applied. In the present IEMCAP case-to-case coupling model, coupling is assumed to change in proportion to D_S^3/D^3 where D is the separation between equipment cases and D_S is the specified distance at which emission measurements were made (generally 1 meter). This inverse-cube-law assumption is used at all frequencies between 14 kHz and 18 GHz, and at all distances greater than 1 meter. No correction (IEMCAP defaults to $D = D_S$) is used in IEMCAP for distance less than 1 meter.

The inverse cube-law asssumption is fairly accurate at separation distances up to 0.1 wavelength. At greater separations, the rate of field attenuation changes rather abruptly to the much lower rate of D_S/D. This means that in the most commonly encountered range between 1 and 10 meters, the inverse cube-law assumption presently used in IEMCAP is only accurate for frequencies below approximately 30 MHz. At higher frequencies, particularly in the microwave and millimeter ranges where typical separation distances can be equivalent to hundreds of wavelengths, levels calculated using the inverse cube-law assumption at 10 meters can be 40 dB too low. This is unfortunate because IEMCAP is supposed to provide a worst-case analysis.

The equations for the fields from small (relative to separation distance, d) dipole and loop antennas are well documented and will be used in the following derivations. The electric field (E-field) generated by a small dipole antenna will be considered first because the E-field is a field component of major importance at all frequencies. The magnetic field (H-field) from

a small loop antenna can be important at low frequencies as a component independent of the E-field when the free-space equation $H = E/377$ breaks down under near-field conditions, and will also be considered for completeness. A distance transfer function will be developed which is independent of the E or H nature of the fields.

The derivations which follow assume transmitting and receiving antennas oriented for maximum coupling and ignore complications, such as reflections and large antennas. There are certain orientations of the transmitting antennas where the far-field ($1/D$) component disappears ($\theta=0^o$) but the near-field ($1/D^2$ and $1/D^3$) components still remain, and certain mutual orientations (cross polarization) where deep nulls occur in the coupling; however the orientational maximums are broad and the nulls are sharp, and may be ignored in a worst-case analysis. Reflections can cause a 6 dB increase in field strength (assuming only one major reflection or a decrease approaching infinity. Again, the increases are locationally broad and decreases locationally sharp so the decreases can be ignored in a worst-case analysis. The possible increase due to constructive reflections can also be ignored under the rationalization that measurements made in a shielded enclosure with the equipment under test (EUT) oriented for maximum emission (or susceptibility) will produce results representative of the intrasystem situation. Certain precautions, such as using shielded enclosures comparable in size to the spaced between reflecting surfaces in the system environment, are in order.

The assumption of small antennas in the following derivations means that the derivations are not applicable to all antennas under all conditions. The derivations are applicable to any antenna in which the current element (incremental distance increments along current carrying conductors, or moments) are close together in comparison to the distance to the field point of interest so that there is no significant difference in the field attentuation rates between current elements. In general, this will be true of any antenna operating in the far-field, or Fraunhofer,

region. A widely accepted criteria for establishing the beginning of the far-field region is that $D_F \geq \ell^2/\lambda$ where D_F is the distance to the field point, ℓ is the maximum dimension of the antenna apperture [4] and λ is the wavelength. At this distance, the antenna gain is 94% of its final far-field value and there are no gain inflection points with increased distance.

The antennas used in the hypothetical Broadband Measurement System are small enough to meet the above far-field criteria at one meter(m). For example, D_F at 100 MHz = 0.8m, at 1 GHz = 0.9m, at 10 GHz = 0.8m and at 18 GHZ = 0.04m. Above 18 GHZ, the System uses waveguide, the current elements are back in the mixers, and the far-field distances for the horn antennas are a few centimeters.

Unfortunately, the equipment under test (EUT) is not nearly so well defined in its roll as an antenna. If the fields emanate from, or enter through, a small well-defined area, then the small antenna criteria will apply and distance extrapolation of field strength will be straight foreward. If in moving the measurement antenna (or susceptible equipment) away from one emanation point on the EUT another emanation point is approached, then difficulties arise. Ideally, dimensions of the EUT should be small in comparison to the measurement distance for the field extrapolation equations to apply with good accuracy. Realistically, the field extrapolation equations probably apply to most EMC situations with sufficient accuracy to be useful.

[4] Silver: "Microwave Antenna Theory and Design," McGraw Hill Radiation Laboratory Series, 1949.

1) E-Field Extrapolation

For an electrically short dipole antenna, the E-field in volts per meter (V/m)at a distance d meters (m) as received on a dipole antenna orthogonal to the directional propagation is[5]:

$$E = \frac{IL\sin\theta}{4\pi\varepsilon}\left[\frac{j\omega}{c^2 d} + \frac{1}{cd^2} + \frac{1}{j\omega d^3}\right] \tag{7}$$

where I is the dipole current in amperes, L is the dipole length in meters, ε is the dielectric constant (permittivity) of the propagation media in farads/m, $\omega = 2\pi f$ where f is the operating frequency in hertz, c is the velocity of light in meters/second, and θ is the angle of propagation relative to the dipole axis.

The ratio of the field measured at a distance d to a field measured at some standard distance d_S is:

$$\frac{E}{E_S} = \frac{\dfrac{j\omega}{c^2 d} + \dfrac{1}{cd^2} + \dfrac{1}{j\omega d^3}}{\dfrac{j\omega}{c^2 d_S} + \dfrac{1}{cd_S^2} + \dfrac{1}{j\omega d_S^3}} \tag{8}$$

Substituting $d = D\lambda$, where D is the separation distance expressed in wavelengths (λ), and taking the standard measurement distance as one wavelength so that $d_S=\lambda$,Equation (8) becomes:

$$\frac{E}{E_\lambda} = \frac{\dfrac{j\omega}{c^2 D\lambda} + \dfrac{1}{cD^2\lambda^2} + \dfrac{1}{j\omega D^3\lambda^3}}{\dfrac{j\omega}{c^2\lambda} + \dfrac{1}{c\lambda^2} + \dfrac{1}{j\omega\lambda^3}}$$

$$= \frac{1}{D^3}\left[\frac{(c^2-\omega^2\lambda^2 D^2)+j(\omega c\lambda D)}{(c^2-\omega^2\lambda^2)+j(\omega c\lambda)}\right]$$

---

[5]Kraus:"Antennas" McGraw-Hill, 1950, page 135.

Taking the magnitude, or absolute value:

$$\left|\frac{E}{E_\lambda}\right| = \frac{1}{D^3}\left[\frac{(c^2-\omega^2\lambda^2D^2)^2 + (\omega c\lambda d)^2}{(c^2-\omega^2\lambda^2)^2 + (\omega c\lambda)^2}\right]^{0.5}$$

Substituting $\omega = 2\pi c/\lambda$:

$$\left|\frac{E}{E_\lambda}\right| = \frac{1}{D^3}\left[\frac{(1-4\pi^2D^2)^2 + (2\pi D)^2}{(1-4\pi^2)^2 + (2\pi)^2}\right]^{0.5}$$

$$= \frac{1}{D^3}\left[\frac{1 - 4\pi^2D^2 + 16\pi^4D^4}{1 - 4\pi^2 + 16\pi^4}\right]^{0.5}$$

$$= \left[\frac{1}{1520\ D^6} - \frac{1}{38.5\ D^4} + \frac{1}{0.976\ D^2}\right]^{0.5}$$

Converting to decibel relationships and setting $-20 \log (E/E_\lambda) = A_\lambda$, the E-field attenuation relative to measurements made at one wavelength is:

$$A_{E\lambda} = -10 \log_{10}\left[\frac{1}{1520\ D^6} - \frac{1}{38.5\ D^4} + \frac{1}{0.976\ D^2}\right] \text{ dB} \quad (9)$$

2) <u>H-Field Extrapolation</u>

For an electrically small loop antenna, the H-field in amperes per meter (A/m) at a distance d meters (m) as received on a parallel loop antenna is[5]

$$H = -\pi nIA \sin\theta \left[\frac{1}{d\lambda^2} + \frac{1}{j2\pi d^2} - \frac{1}{4\pi^2 d^3}\right] \quad (10)$$

where n is the number of turns, I is the current in amperes, A is the area in square meters, θ is the angle between the loop axis and the receiver, d is the separation distance in meters and λ is the wavelength in meters.

[6] Shelkunoff: "Antennas-Theory and Practice," Wiley, 1952 page 320 (notation altered).

The ratio of the field measured at a distance d to the field measured at some standard distance d_S is:

$$\frac{H}{H_S} = \frac{\dfrac{1}{d\lambda^2} + \dfrac{1}{j2\pi d^2\lambda} - \dfrac{1}{4\pi^2 d^3}}{\dfrac{1}{d_S\lambda^2} + \dfrac{1}{j2\pi d_S^2\lambda} - \dfrac{1}{4\pi^2 d_S^3}} \qquad (11)$$

Substituting $d = D\lambda$ where D is the separation distance expressed in wavelength (λ), and taking the standard measurement distance as one wavelength so that $d_S=\lambda$, Equation (11) becomes:

$$\frac{H}{H_S} = \frac{\dfrac{1}{D\lambda^3} + \dfrac{1}{j2\pi D^2\lambda^3} - \dfrac{1}{4\pi^2 D^3\lambda^3}}{\dfrac{1}{\lambda^3} + \dfrac{1}{j2\pi\lambda^3} - \dfrac{1}{4\pi^2\lambda^3}}$$

$$= \frac{4\pi^2 D^2 - j2\pi D - 1}{4\pi^2 D^3 - j2\pi D^3 - D^3}$$

$$= \frac{1}{D^3}\left[\frac{(4\pi^2 D^2 - 1) - j(2\pi D)}{(4\pi^2 - 1) - j(2\pi)}\right]$$

Taking the magnitude, or absolute value

$$\left|\frac{H}{H_S}\right| = \frac{1}{D^3}\left[\frac{(4\pi^2 D^2 - 1)^2 + (2\pi d)^2}{(4\pi^2 - 1)^2 + (2\pi)^2}\right]^{0.5}$$

$$= \frac{1}{D^3}\left[\frac{16\pi^4 D^4 - 4\pi^2 D^2 + 1}{16\pi^4 - 4\pi^2 + 1}\right]^{0.5}$$

$$= \left[\frac{1}{1520\ D^6} - \frac{1}{38.5\ D^4} + \frac{1}{0.976\ D^2}\right]^{0.5}$$

Converting to decibel relationships and setting $-20 \log_{10}(H/H_S) = A_{H\lambda}$, the H-field attenuation relative to measurements made at one wavelength is:

$$A_{H\lambda} = -10 \log_{10} \left[\frac{1}{1520\ D^6} - \frac{1}{38.5\ D^4} + \frac{1}{0.976\ D^2}\right] \text{dB} \qquad (12)$$

which is identical to Equation (9) for the E-field. Distance equations to be developed in the next Subsection will apply equally to the E and H fields.

3) <u>Distance Transfer Function</u>

Taking into account the square-root submerged in the decibel conversion, Equations(9) and (12) contain three terms, the first varying as $1/D^3$, the second as $1/D^2$ and the third as $1/D$. The transition from $1/D^3$ to $1/D$ occurs when $1520\ D^6 = 0.976\ D^2$, or at $D_{3/1}=0.1592\lambda$. The contribution of the $1/D^2$ term is very small and may be neglected with only 1.2 dB peak error as illustrated in Figure 8, in which the difference between Equations (9) or (12), with and without the middle term, is plotted.

The abscissa in Figure 8 is in terms of a new and useful quantity, the dBλ. The defining equation is:

$$\text{dB}\lambda = 20 \log_{10} D \qquad (13)$$

which is simply distance in wavelengths expressed in decibels. Using the dBλ, exact field extrapolation values needed can be obtained quite simply without having to solve a cubic equation.

Starting with the inverse-cube-law to inverse-first-power-law transition, $D_{3/1}=0.1592\lambda=-16.0$ dBλ, a check is first made to see if a given separation distance is in the inverse-cube-law or inverse-first-power-law region. This is done by calculating the separation distance d, in dBλ as:

$$20 \log_{10} D = 20 \log_{10} d + 20 \log_{10} f_{MHz} - 49.5 \text{ dB}\lambda \qquad (14)$$

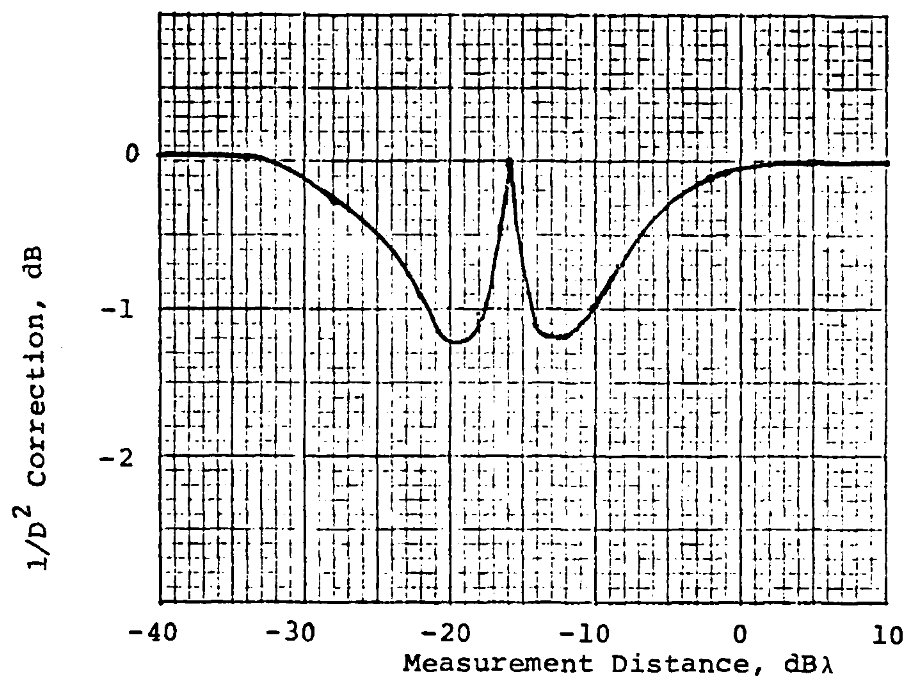


Figure 8 Correction To Include $1/D^2$ Factor

where d is the given separation distance in meters and f_{MHz} is the frequency in MHz. The constant -49.5 includes the velocity of light and the conversion from Hz to MHz. If $20 \log_{10} D$ is less than -16.0 dBλ, D is in the inverse cube law region. If $20 \log_{10} D$ is greater than -16.0 dBλ, D is in the inverse first-power-law (inverse-distance) region.

Next, the same thing is done with the standard measurement distance, d_S, at which the measurements to be extrapolated were made. This time:

$$20 \log_{10} D_S = 20 \log_{10} d_S + 20 \log_{10} f_{MHz} - 49.5 \text{ dB}\lambda \qquad (15)$$

or, if the standard measurement distance is 1 meter:

$$20 \log_{10} D_S = 20 \log_{10} f_{MHz} - 49.5 \text{ dB}\lambda \qquad (16)$$

Again, if $20 \log_{10} D_S$ is less than -16.0 dBλ, the measurements were made in the inverse-cube-law region, and if greater, in the inverse-distance region.

Using D and D_S in decibels from Equations (14) and (15), the distance transfer function, T_d, can then be calculated as:

$$\begin{aligned} T_d &= mD_S + (m-1)(15.9) - nD - (n-1)(15.9) \\ &\quad - C_m + C_n \\ &= mD_S - nD + 15.9(m-n) - C_m + C_n \text{ dB} \qquad (17) \end{aligned}$$

where:

$n = 3$ if $D \leq -16$ dBλ, or $n=1$ if $D > -16$ dBλ

$m = 3$ if $D_S \leq -16$ dBλ, or $m=1$ if $D_S > -16$ dBλ

The constant 15.9 is a scale factor derived from Equation (9) by taking the square root of the first term ($-5 \log_{10} 1/1520 = 15.9$ dB). The inverse-square law correction factors C_m and C_n are obtained by entering D_S and D on Figure 8. (C_m and C_n can be neglected with only 1.2 dB maximum error.) Adding T_d in dB to the field strength in dBμV/m, dBμV/m/MHz, or dBμA/m measured at the standard distance, d_S, in meters (usually 1 meter) gives the field strength at the new distance, d, in meters.

As an example, consider an emission measurement of 67 dBμV/m made at 10 MHz under standard conditions at 1 meter. It is desired to know the field strength that would exist at 10 meters. Using Equation (14):

$$20 \log_{10} D = 20 \log_{10} 10 + 20 \log_{10} 10 - 49.5$$
$$= 20 + 20 - 49.5$$
$$= -9.5 \text{ dB}\lambda$$

which is greater than -16 dBλ and therefore in the inverse-distance region for which n=1.

The standard measurement distance in dBλ, using Equation (16) is:

$$20 \log_{10} D_S = 20 \log_{10} 10 - 49.5$$
$$= 20 - 49.5$$
$$= -29.5 \text{ dB}\lambda$$

which is less than -16 dBλ and therefore in the inverse-cube-law region for which m=3.

Using Equation (17), the distance transfer function for this example is calculated as:

$$T_d = 3(-29.5) - 1(-9.5) + 15.9(3-1) - (-0.2) + (-0.9)$$
$$= -88.5 + 9.5 + 31.8 + 0.2 - 0.9$$
$$= -47.9 \text{ dB}$$

which agrees closely with the value of -47.8 dB calculated using Equation (8) as a check. The field strength extrapolated to 10 meters is thus 67 - 47.9 = 19.1 dBμV/m, or 19 dBμV/m keeping only the significant figures in the original data.

For comparison, the inverse-cube-law assumption presently used in IEMCAP would give $T_d = 20 \log_{10} D_S^3 = 20 \log_{10} 1/10^3 =$ -60 dB. The extrapolated field strength would be 67 - 60 = 7 dBμV/m, which would be 12 dB too low.

D. Measurement Techniques - Automated and Broadband Systems

As discussed in the third quarterly report, certain MIL-STD-461A test requirements do not allow for automated or broadband test techniques. In general, the tests that fall into this category are those for susceptibility. Table 12 of the Third Quarterly Report lists instances where automated or broadband test techniques cannot be used. In these instances, the best alternative is to revert to MIL-STD-462 measurement procedures, which are essentially manual. However, if there is a way to automatically monitor the equipment under test for degradation effects, then the test may be automated or semi-automated by using Swept sources. Broadband impulse testing is used for determination of susceptibility to electromagnetic pulses (EMP) in terms of survivability, but such techniques have not been applied in EMC testing.

A review of various commercially available automated EMI/EMC measurement systems was conducted. The systems reviewed were built by Fairchild (now Electro-Metrics Division of Penril Corp.), Watkins-Johnson, or put together from available test components such as a computer, receiver, calibration devices and display unit. The upper frequency for most systems is either 1 or 10 GHz. Emission testing is the only test function that can be performed in the automated mode. The savings in time and manpower for emission testing is impressive. The data results may be plotted out in final technical report quality by the automated system.

APPENDIX I

PROPOSED DRAFT INTRASYSTEM MEASUREMENT STANDARD

MIL-STD-
15 June 1980

MILITARY STANDARD
INTRASYSTEM ELECTROMAGNETIC CHARACTERISTICS
REQUIREMENTS

Forward

The purpose of this Standard is to provide uniform guidelines to all Department of Defense Agencies for the Electromagnetic test requirements and specification levels for all systems containing electronic and electrical equipments. The Standard provides for the use of computer-based analytical techniques for the computation of intrasystem electromagnetic compatibility (EMC) parameters. Actual testing will be performed at frequencies and system points that are revealed as problem areas by the analytical programs. The criteria for selecting these parameters are described in the Standard. The results of the use of this Standard will be the compatible electromagnetic performance of electronic and electrical equipment when assembled into a system.

1. SCOPE

1.1 Scope - This Standard covers the requirements and test limits for the analysis and measurement of the intrasystem electromagnetic interference characteristics of military systems. This includes the electromagnetic environment created by the system and the external environment the system is expected to operate in.

1.1.1 The requirements specified in this Standard are established to:

(a) Insure that interference control is considered and incorporated into the design of a system.

(b) Enable compatible operation of the system in a complex electromagnetic environment.

1.1.2 This Standard shall be used in conjunction with analytical computer-based electromagnetic prediction programs. The data used as inputs to the program will be obtained from measurement or modeling techniques used on the individual equipments in the system.

1.2 Units - This Standard requires use of the International System of Units as specified in MIL-STD-463.

2. REFERENCE DOCUMENTS

2.1 The following documents of the issue on date of invitation for bids or request for proposal, form a part of this Standard to the extent specified herein:

SPECIFICATIONS

MILITARY

MIL-C-45662 - Calibration of Standards.

STANDARDS

MILITARY

MIL-STD-461 - Electromagnetic Interference Characteristics Requirements For Equipment

MIL-STD-462 - Electromagnetic Interference Characteristics, Measurement of

MIL-STD-463 - Definitions and Systems of Units, Electromagnetic Interference Technology

MIL-STD-633 - Mobile Electic Power Engine Generator Set Family.

MIL-STD-831 - Test Reports, Preparation of

2.2 Other Publications - The documents referenced below form a part of this Standard to the extent specified herein. Unless otherwise specified in the individual equipment specification, the issues of these documents in effect on date-of-invitation for bids or requirests for proposals shall apply.

SOCIETY OF AUTOMOTIVE ENGINEERS, INC. (SAE)

SAE-ARP-936 - Ten microfarad Capacitor

SAE-ARP-958 - Measurement of Antenna Factors

SAE-J551 - Measurement of Vehicle Radio Interference (30 to 400 MC)

2.3 Computer Programs for the Prediction of Intrasystem Electromagnetic Interference - The following is a list of accepted analytical programs that may be used with this Standard:

IEMCAP

:

:

:

ETC. (To be expanded as computer-based EMC programs become available.)

3. DEFINITION - The terms used in this Standard are defined in MIL-STD-463.

4. GENERAL REQUIREMENTS

4.1 Application of Standard - The requirements of this Standard shall be applied to systems that contain electronic, electrical and electromechanical equipments as described in the following paragraphs.

4.1.1 <u>Systems</u> - A system is a complex of individual components integrated as a whole to provide a desired function. The individual components may be electronic, electrical or electromechanical devices. Examples of systems are aircraft, tanks, ships, computer controlled missiles, etc.

4.1.2 <u>Equipments</u> - Equipments as described in this Standard are either electronic, electrical or electromechanical devices. Each equipment in the system under consideration in this Standard should have a complete electromagnetic data package based on the equipment class as defined in MIL-STD-461, Table 1.

4.1.3 <u>Equipments Without Electromagnetic Data</u> - When equipments are to be included in the system that have not been tested to MIL-STD-461, then either the equipments should be tested (approved broadband methods may be used) before system evaluation under this Standard, or if this is not feasible, then the electromagnetic characteristics of the equipment should be modeled by a competent agency and used under this Standard. If the characteristics are modeled then the emission and susceptibility threshold levels are made more stringent during the analytical phase.

4.1.4 <u>System Data Required</u> - Accurate mechanical and electrical drawings of the system shall be available for the analytical phase of system test. All EMI/EMC engineering design data from the manufacturer of the system shall be made available to the test agency. This shall include EMI/EMC control, frequency management, wiring and circuit design, and the results of any preliminary EMI/EMC testing or analysis.

4.1.5 <u>System EMI/EMC Limits</u> - The limits under this Standard are not fixed values but are based on the threshold levels of susceptibility of the individual equipments that make up the system, the electromagnetic environment that is generated by the system equipments, and the external electromagnetic environment that the system shall operate in.

4.1.5.1 Susceptibility - The limits shall be based on the MIL-STD-461 data package for the individual equipments. Limits shall be expressed for both conducted and radiated susceptibility levels over a frequency range. The conducted limits shall be specified for both the power and signal lines of the equipment. The radiated limits shall be specified at radius of one meter from the equipment.

4.1.5.2 Emission - The limits shall be based on the MIL-STD-461 data package for the individual equipments. The emission levels shall be compared to the susceptibility levels of all potentially susceptible equipment in the system. Emission levels in the environment that the system is to operate in shall also be compared to the susceptibility levels.

4.1.5.3 Limit Conformance Using Analytical Technique - One of the computer programs specified in Section 2.3 shall be used to determine conformance to the conducted and radiated susceptibility and emission limit levels. If MIL-STD-461 data has been used in the computer program for all of the system equipments, and susceptibility/emission margins are calculated to be at least 10 dB, no further testing is required and the system is considered compatible. If MIL-STD-461 data packages were not available for all equipments, then the calculated susceptibility/emission margins with respect to those equipments must be at least 20 dB to obviate further testing.

4.2 EMI/EMC System Analysis and Test Plan - The system analysis and test plan shall detail the means and application of the analytical and test procedures. The plan shall include but not be limited to the following:

(1) Description of the analytical computer program to be used.

(2) The MIL-STD-461 data package available for each of the equipments in the system.

(3) The susceptibility and emission level limits (both conducted and radiated) for each equipment. This shall be described graphically from 14 kHz to 100 GHz in units of dBμA for conducted levels and dBμV/m or dBμA/m for radiated levels.

(4) The expected electromagnetic environment for the system. This shall be described from 14 kHz to 100 GHz in terms of dBμV/m or dBμA/m

(5) The criteria that shall be used to determine whether system EMC/EMI testing shall be necessary.

(6) If testing is necessary, the criteria that shall be used to determine test points, frequency ranges, and test requirements.

(7) Test techniques to be used:
   (a) Conventional
   (b) Automated
   (c) Broadband

(8) The resources necessary to perform the testing in terms of test instrumentation, personnel and time.

(9) Detailed step-by-step test procedures and test setups describing the test techniques to be used.

(10) An accuracy analysis for the test procedure elected.

(11) A matrix describing the limit levels for each equipment in the system versus frequency. This shall be prepared for both conducted and radiated conditions.

(12) Nomenclature, serial numbers and pertenent characteristics of test equipment (for example, transfer impedance of current probes and antenna factors for antennas).

(13) Methods and dates of last calibration of interference measuring equipment and calculations to show expected accuracy of each in conformance with MIL-C-45662.

(14) Dummy loads, filters, dummy antennas, signal samplers, and similar items to be used and their description (for example, VSWR, isolation and loss) in the frequency range of interest. In addition, a tabular or graphical plot of the complex impedance at selected test frequencies of all reactive loads used shall be included.

(15) Readout and detector functions to be used in measuring equipment, where applicable.

(16) Nomenclature, description and modes of operation of the system under test.

4.3 System Analysis and Test Report Format

4.3.1 The format of the report shall be as specified in MIL-STD-831.

4.3.1.1 Cover Page - A cover page is required.

4.3.1.2 A separate appendix shall be utilized for each function required by this Standard. An appendix will describe in detail the analytical program used in the task. Appendices shall include the analytical results, test procedures, original data sheets, graphics, illustrations and photographs. Definition of specialized terms or word usage shall also be included in a separate appendix.

4.3.2 Content - The technical report shall contain the factual data in conformance with this Standard and MIL-STD-831. The report shall be divided into two major sections, analysis and measurements. The analytical results shall be presented and the rationale for either continuing into the measurement phase or not, presented. The measurement phase shall be completely described along with the reasons for selection of a particular measurement technique. Details of the measurement procedures shall be presented in a form similar to that required for MIL-STD-461 testing. Measurement results shall be summarized in the body of the report. All raw data shall be included in an appendix of the report.

5. DETAILED REQUIREMENTS

5.1 Analytical Programs

A requirement of the analytical program is that it have the following capability:

(1) Frequency range 14 kHz - 100 GHz.

(2) Accuracy ± 2 dB for both conducted and radiated emission.

(3) Capacity to handle the number of test points required for the system under test.

(4) Capacity to handle the number of equipments in the system and the complexity of their electromagnetic signature.

(5) An output format that will expedite the decision making process with respect to system EMI/EMC measurements.

5.2 Measurement Procedures

Measurement procedures shall be described in the EMI/EMC System Analysis and Test Plan. Techniques described shall produce the required data. Frequency accuracy shall be $\pm 2\%$ and amplitude accuracy shall be ± 2 dB. The number of test points, frequency range and limit levels shall be determined from the analytical results. The test instrumentation and techniques shall be capable of providing this data.

5.3 Limit Levels

When measurements are performed, the limit levels are the exact susceptibility levels of the individual equipments. The frequency range of susceptible responses found by analysis or measurement shall be considered to extend above and below the center frequency of the response by $\pm 20\%$, or by the actual susceptibility profile, whichever is greater.

APPENDIX II
RECOMMENDED TEST PROGRAM

1. RECOMMENDATION

A test program is recommended to demonstrate the feasibility of the draft Intrasystem Measurement Standard by application to a typical system, and to experimentally prove the broadband measurement techniques can provide a significant portion of the electrical data required for implementation of the Standard.

2. PROOF OF BROADBAND MEASUREMENT SYSTEM PRINCIPLES

A breadboard model of one band of the Broadband Measurement System for radiated emissions shall be assembled and demonstrated. The band to be demonstrated shall be selected as appropriate to one or more of the C-E equipments included in the data base assembled in Section 2 of this Appendix. The equipments on which the selection is based shall be available for laboratory testing.

The demonstration equipments shall have MIL-STD-461 profiles over the frequency range of the band selected. If these profiles are pre-existing, they shall be verified in the actual demonstration setup to assure validity.

Measurements shall be made on the demonstration equipment with the Broadband Measurement System and the results correlated with the MIL-STD-461 data obtained with standard test equipment. Response to both narrowband and broadband emissions shall be demonstrated.

Measurements shall also be performed and documented on the breadboard Broadband Measurement System using standard test equipment to demonstrate sensitivity, frequency response, broadband-to-narrowband response ratio, dynamic range, response to various modulations and response to multiple signals.

3. FEASIBILITY DEOMONSTRATION OF DRAFT INTRASYSTEM MEASUREMENT STANDARD

A suitable system shall be selected for application of the draft Intrasystem Measurement Standard. The choice shall consider such factors as the handling of and access to classified information; the availability of adequate design information such as dimensional drawings detailed equipment locations, wire runs, etc.; availability of EMI profiles on equipments in the system as obtained from MIL-STD-461 or similar measurements; and availability of equipments in the system and the system itself for laboratory or field testing.

The draft Intrasystem Measurements Standard shall be applied to the system selected. A data base shall be assembled suitable for IEMCAP anlaysis. Dimensional data shall be taken from drawings, or measured in-situ. Electrical data shall be taken from equipment manuals, records of MIL-STD-461 measurements, or obtained by laboratory measurements in accordance with MIL-STD-461. Key items of equipment shall be available later for laboratory verification of MIL-STD-461 results using the Broadband Measurement System breadboard.

The system selected shall be tested for intrasystem EMC. A test plan shall be prepared for demonstration of the degree of EMC within the communications-electronic (C-E) equipment as installed. All systems considered shall be fully operational and shall be operated in all likely combinations. Existance of EMC shall be considered demonstrated when any given C-E equipment operates without significant malfunction. Any malfunctions observed shall be documented and compared with performance predicted by analysis in accordance with the Standard. Any malfunctions predicted but not observed shall also be documented.

APPENDIX III

Control Microcomputer Software Flow Diagram for Hypothetical Broadband Measurement System

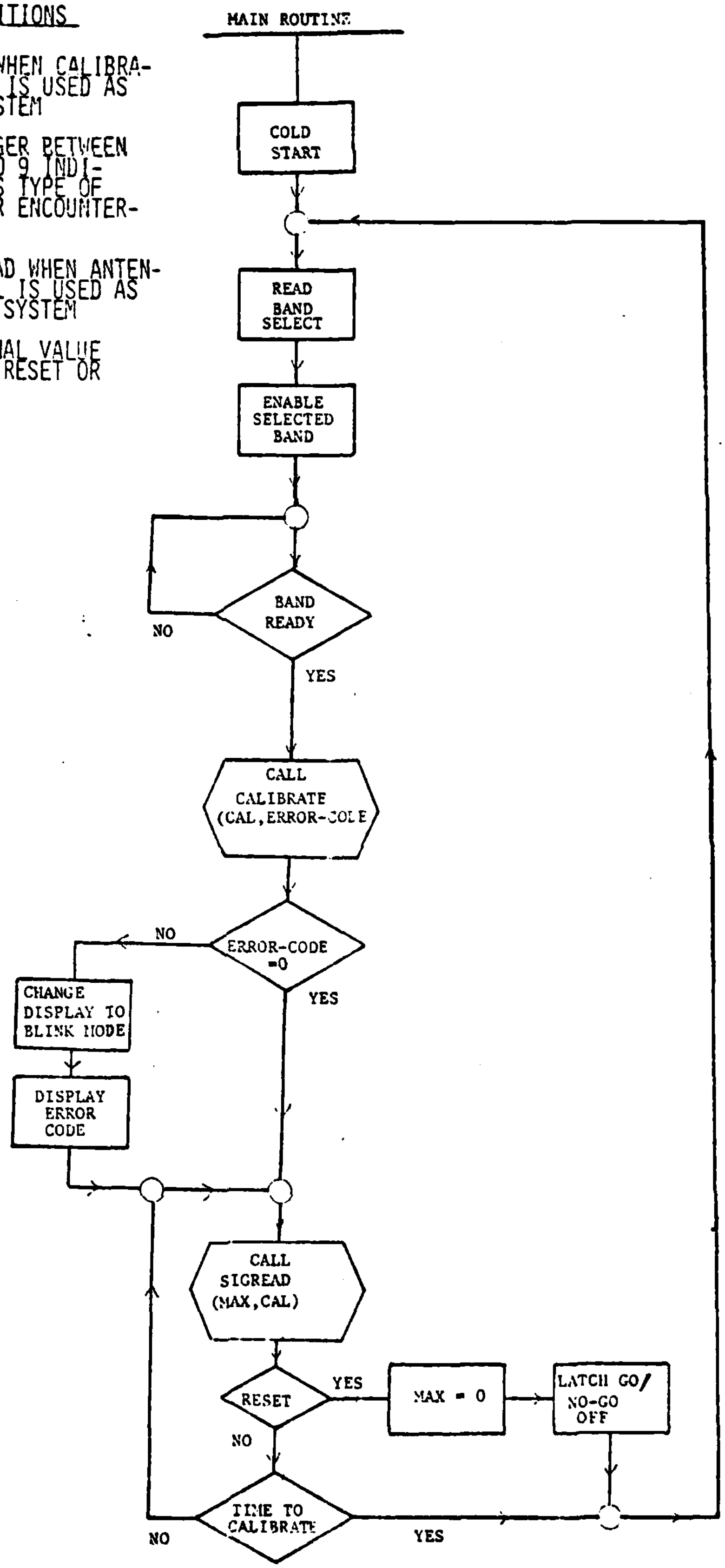
VARIABLE DEFINITIONS

CAL: LEVEL READ WHEN CALIBRATION SIGNAL IS USED AS INPUT TO SYSTEM

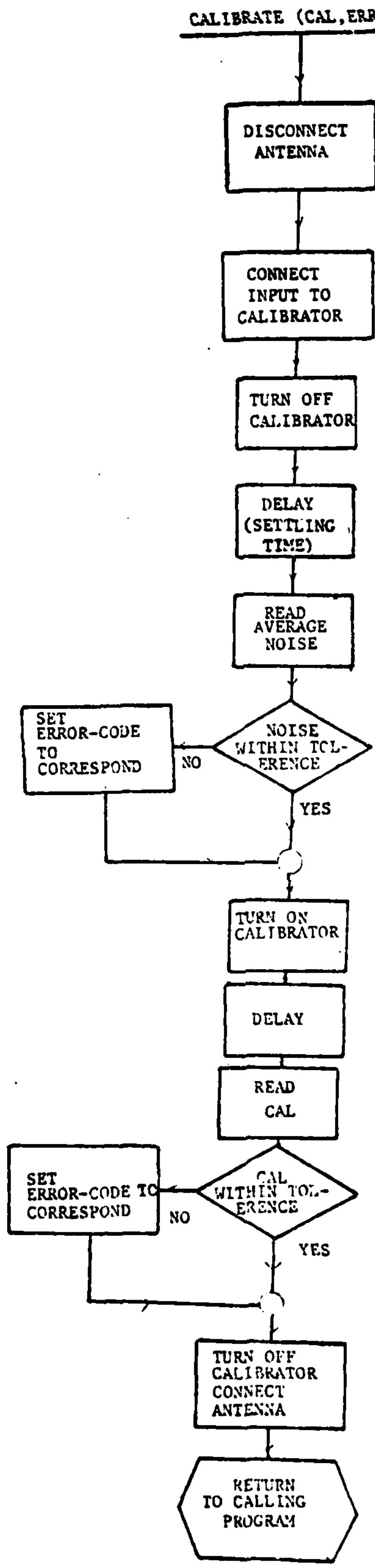
ERROR-CODE: INTEGER BETWEEN Ø AND 9 INDICATES TYPE OF ERROR ENCOUNTERED

SIGNAL: LEVEL READ WHEN ANTENNA SIGNAL IS USED AS INPUT TO SYSTEM

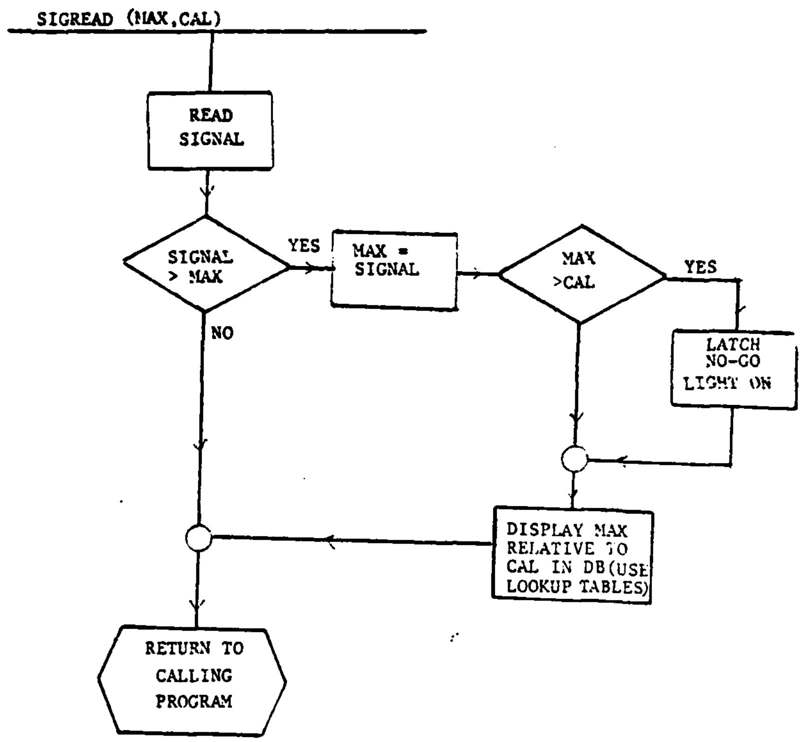
MAX: MAXIMUM SIGNAL VALUE FOLLOWING A RESET OR COLD START



Control Microcomputer Software Flow Diagram for Hypothetical Broadband Measurement System.



Control Microcomputer Software Flow Diagram for Hypothetical Broadband Measurement System (Continued)



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